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TM 11-665

DEPARTMENT OF THE ARMY TECHNICAL MANUAL

C-W AND A-M RADIO TRANSMITTERS AND RECEIVERS

This reprint includes all changes in effect at the time of publication; change 2.

DEPARTMENT OF THE ARMY • SEPTEMBER 1952

TECHNICAL MANUAL

C-W AND A-M RADIO TRANSMITTERS AND RECEIVERS

TM 11-665
CHANGES NO. 2

HEADQUARTERS,
DEPARTMENT OF THE ARMY
WASHINGTON 25, D. C., *22 July 1960*

TM 11-665, 6 September 1952, is changed as follows:

Page 81, paragraph 55*a*(1), line 1. (as changed by C 1, 16 Apr 58) Change "transmitted" to: **transmitter.**

Page 86, paragraph 57*c*(1), line 5. (as changed by C 1, 16 Apr 58) Change "cc" to: **Cc.**

Page 111, paragraph 71*a*(1), line 41. (as changed by C 1, 16 Apr 58) Change "5,000.5 kc" to: **5,005 kc.**

Page 134, paragraph 79*d*(1)(*a*), formula. (as changed by C 1, 16 Apr 58) Change "R_p" to: r_p.

Page 144, paragraph 81c(2), first sentence. (as changed by C 1, 16 Apr 58) Change "V1 and V2" to: **V2 and V3.**

Page 182, Paragraph 113*b*(3), last sentence. (as changed by C 1, 16 Apr 58) Add "than provided by" after "voltage".

Page 217. Add paragraphs 141.1 and 141.2 after paragraph 141:

141.1 Magnetostrictive Electromechanical Filters

a. General (figs. 188.1–188.3). A magnetostrictive electromechanical filter is a mechanically resonant device that receives RF energy at its input end, converts the RF energy into corresponding mechanical vibrations, and then converts the mechanical vibrations back into RF energy at its output end. A high degree of selectivity, far surpassing that obtained by the use of if transformers, is possible by using a magnetostrictive electromechanical filter. The filter is usually designed to have center frequencies that range from 60 to 600 kc. Basically, the electromechanical filter consists of an input and an output transducer (electrically and physically identical) and a resonant mechanical device. The complete unit is hermetically sealed in a metal container.

b. Typical Construction. Figure 188.4 illustrates the typical construction of electromechanical filters with disk, plate, and neck-coupled mechanical resonators. All three types use transducers to convert RF energy into mechanical vibrations, and mechanical vibrations back into electrical energy.

(1) A typical plate-type electromechanical filter is shown in figure 188.1 and in A, figure 188.4. This type of filter consists of an input and an output biasing magnet, an input and an output transducer coil, an input and an output rectangular nickel transducer plate, rectangular stainless-steel resonators, and pairs of nonresonant metal coupling rods. The transducer plate is contained inside the coil windings. Two nonresonant metal rods spot-welded between the transducer plate and the adjacent plate resonator, provide mechanical coupling between these plates. Each plate resonator, in turn, is connected by a pair of steel rods to a following plate resonator. The entire filter structure is placed between the linings of a soft substance, such as cloth or neoprene, and hermetically sealed in a flat metal container.

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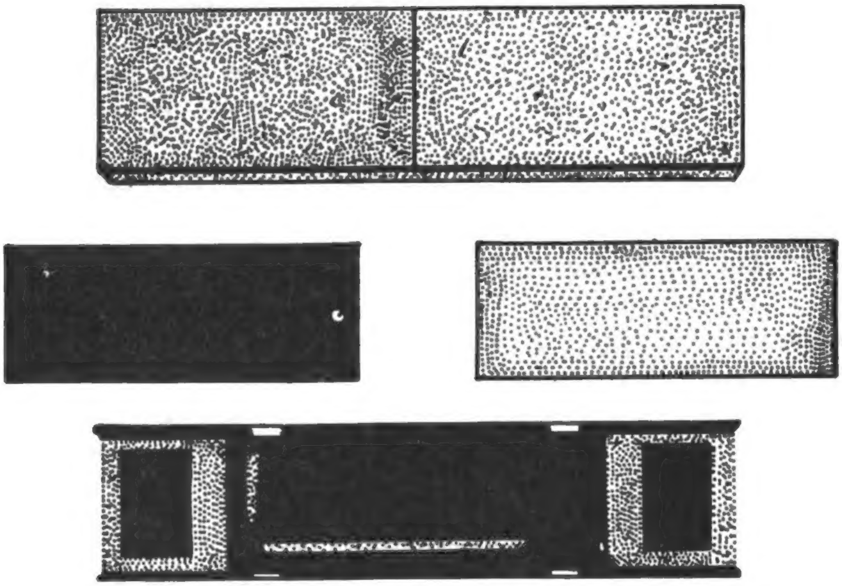
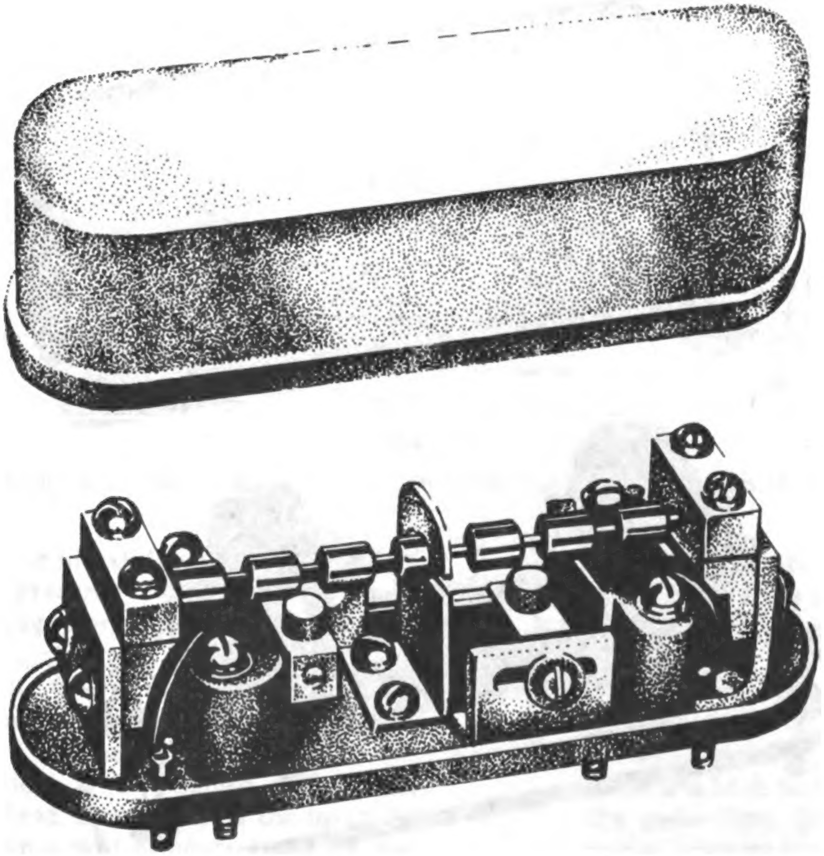
* These changes supersede C 1, 16 April 1958.



TM663-C2-5

Figure 188.1. (Added) *Typical plate-type electromechanical filter.*

(2) A neck-coupled, torsional-type electromechanical filter is shown in figure 188.2 and in B, figure 188.4. It consists of two identical transducer units, cylindrical resonators, coupling rods, and two biasing magnets. Each transducer consists of two windings, and two ferrite rods (magnetic ceramic material having negligible eddy current losses). One ferrite rod, contained inside one winding, is spot-welded to one side of a resonator. The other rod, contained inside the other winding, is spot-welded to the other side of the same resonator. The resonators, and the coupling rods between them, are precision-machined from a solid metal rod. In the assembled filter, the resonator rod is securely held in place by a clamp on each end.



TM665-C2-8

Figure 188.2.* (Added) *Typical neck-coupled torsional-type electromechanical filter.

(3) A disk-type electromechanical filter is shown in figure 188.3 and also in C, figure 188.4. Each transducer consists of a biasing magnet, coil, and pure nickel rod. The input transducer rod, contained inside the transducer coil, is spot-welded to the second disk of a series of metal disk resonators. The output transducer rod, contained inside the output transducer coil, is spot-welded to a disk second from the end. A nonresonant disk at each end provides support for the entire disk assembly. All the disks are mechanically coupled to each other by three metal rods spot-welded to the edge of each disk.

c. Operating Principle of Typical Input Transducer. The operation of an input transducer (fig. 188.5) is based on the principle of magnetostriction—the ability of a magnetic

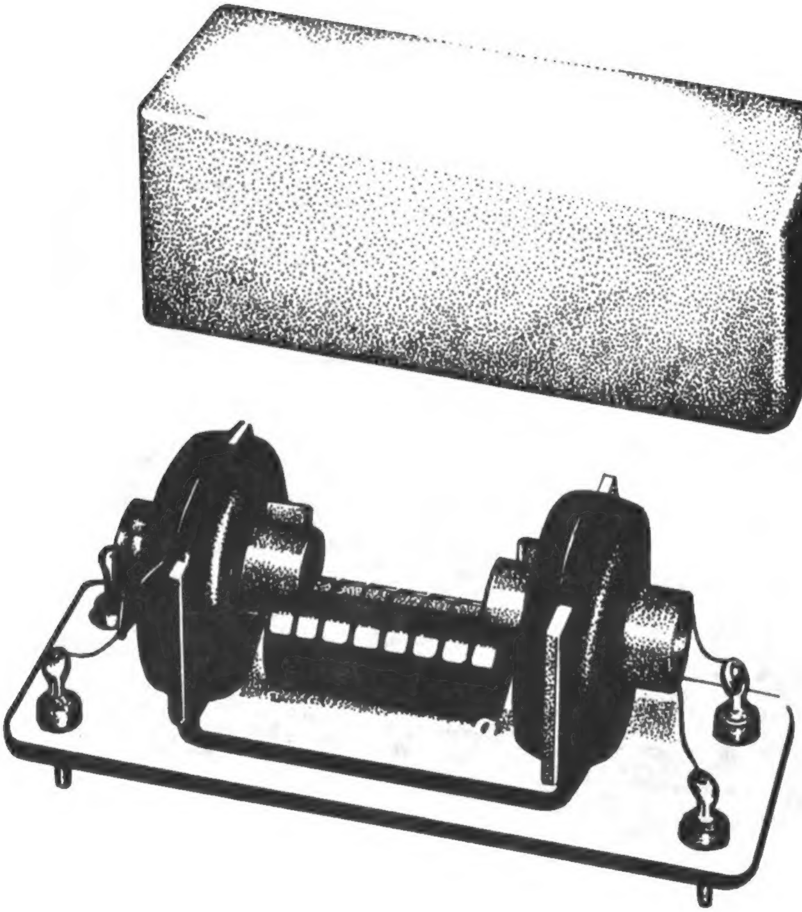


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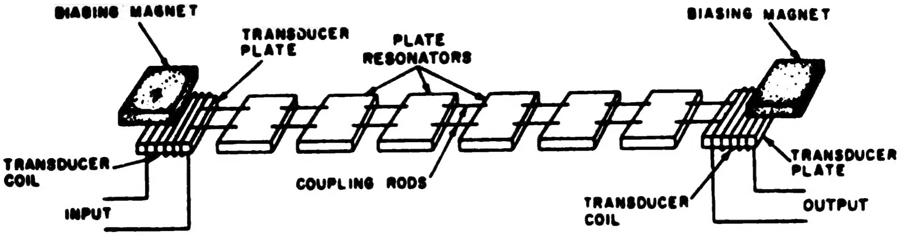
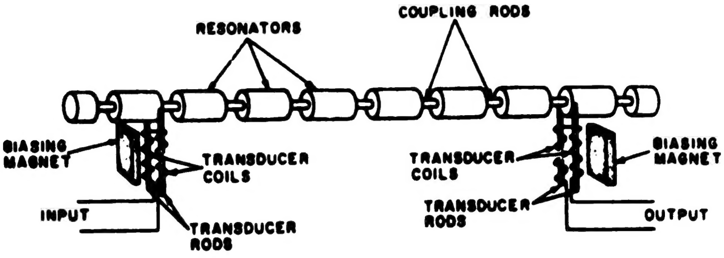
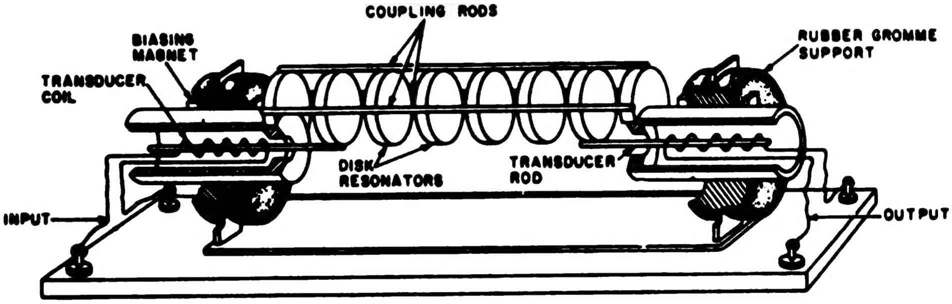
Figure 188.3. **(Added)** ***Typical disk-type electromechanical filter.***



A. PLATE TYPE



B. NECK-COUPLED TORSIONAL-TYPE



C. DISK TYPE

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Figure 188.4. **(Added)** ***Typical construction of various types of electromechanical filters.***

substance, such as nickel, to elongate or shorten when in the presence of a magnetic field. Whether a magnetostrictive substance will shorten or elongate from its normal position when a magnetic field is applied will be determined by the type of material used and not by the direction of the magnetic field. In the following discussion, it is assumed that in the presence of a fixed magnetic field the magnetostrictive substance will elongate from its normal position.

(1) When a permanent magnet is placed near the magnetostrictive rod (A, fig. 188.5), the rod lengthens to a bias point determined by the strength of the magnetic field. The magnet exerts a permanent force on the rod. If a coil is wound around the rod (B, fig. 188.5), and a positive half-cycle of current flows through the coil, the current will produce a magnetic field that adds to the magnetic field of the biasing magnet. As the input current varies from 0 to maximum and back to 0, the strength of the magnetic field varies from its original value to maximum and back to its original value. At the same time, the length of the rod varies from its bias point to maximum and back to its bias point. As the current through the coil (C, fig. 188.5) varies from 0 to maximum in a direction opposite to that in B and back to 0 during the negative half-cycle, it produces a magnetic field that opposes the magnetic field of the biasing magnet. As the strength of the magnetic field varies from its original value to

minimum and back to its original value, the length of the rod varies from its bias point to minimum and back to its bias point. One complete cycle is shown in D, figure 188.5. The movement of the rod, which corresponds to the amplitude and frequency of the input current, is actually a sinusoidal displacement about a fixed bias point.

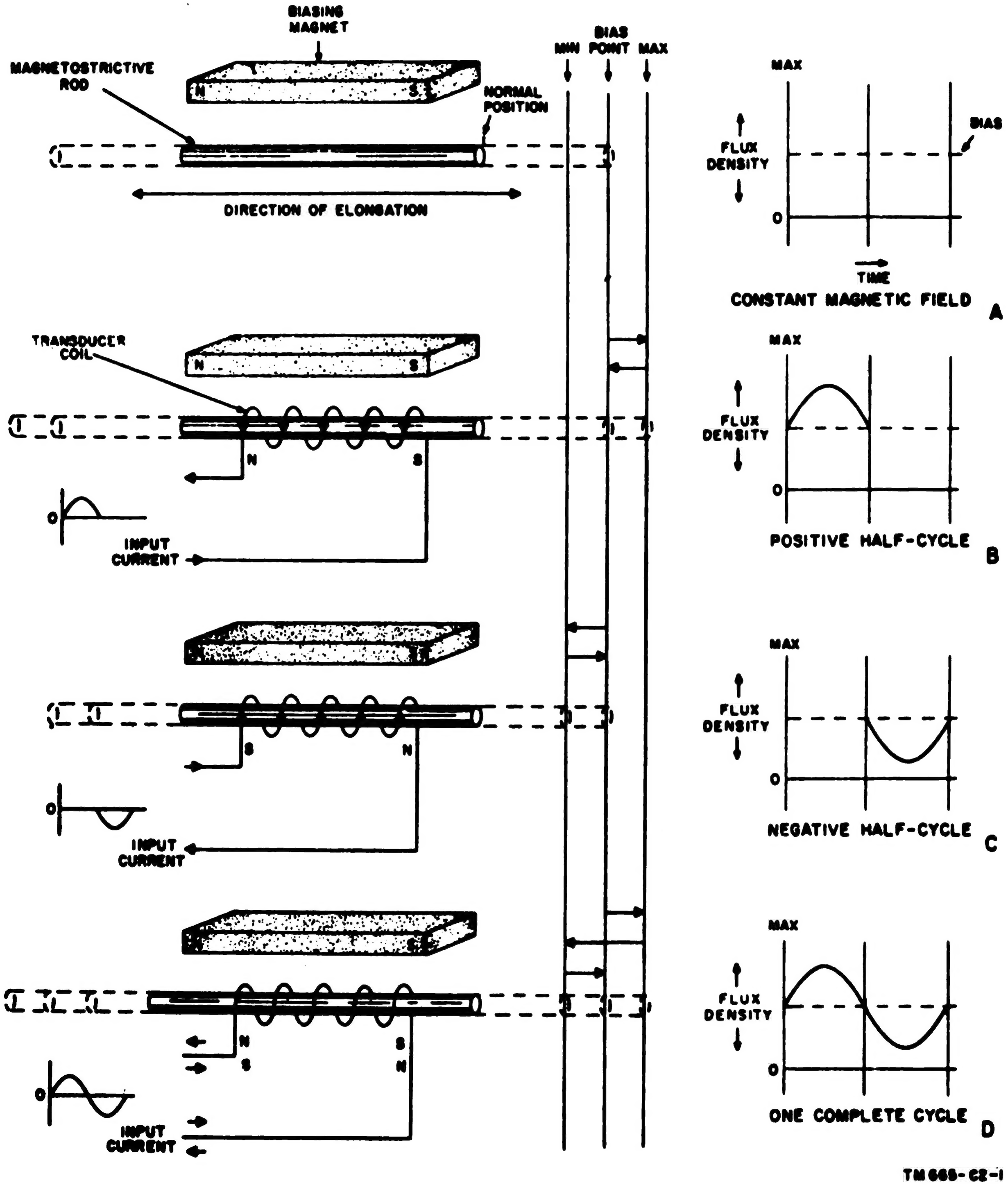


Figure 188.5. (Added) *Typical operation of a magnetostrictive rod.*

(2) Operation of the magnetostrictive rod without a biasing magnet will cause a frequency-doubling action that generates two mechanical cycles for each electrical cycle. Therefore, the transducer output will have a fundamental frequency twice that of the input current and will also be distorted. Figure 188.6 illustrates the transducer without its biasing magnet. In A, figure 188.6, there is no current flow in the coil; therefore the magnetostrictive rod remains at its normal length. When a sinusodial current flows in the coil during the positive half-cycle, as in B, figure 188.6, a magnetic field of similar variations is produced. This field causes the rod to lengthen to a maximum length, and return to its normal length. The polarity of the magnetic field (C, fig. 188.6) is reversed during the negative half-cycle; however, regardless of the polarity of the magnetic field, the rod lengthens as in B. The rod lengthens for both half-cycles of current instead of alternately lengthening and shortening as described in (1) above. During the complete input cycle (D, fig. 188.6), a fundamental mechanical frequency twice that of the input current is produced.

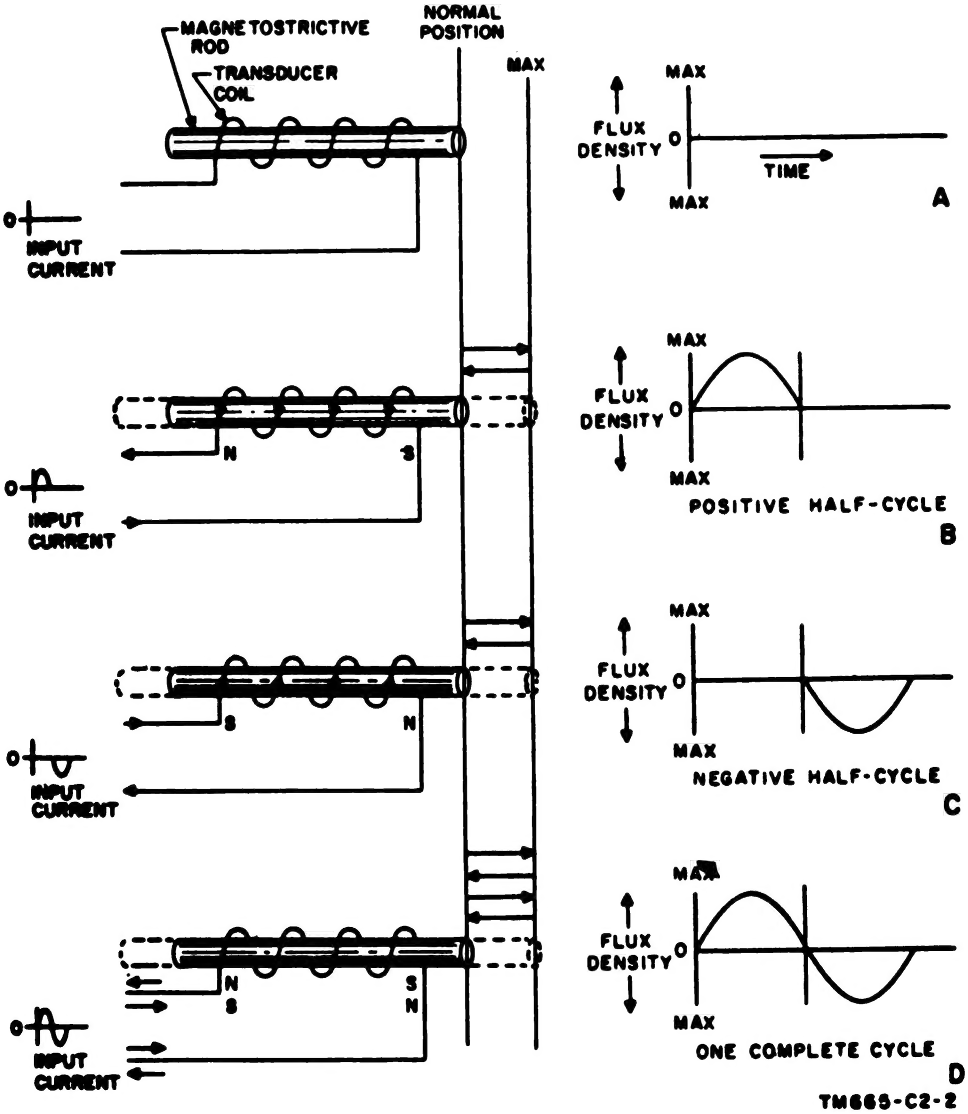


Figure 188.6 (Added) *Operation of a magnetostrictive rod without a biasing magnet.*

d. Disk-type Electromechanical Filter (figs. 188.2 and 188.4). If an RF signal is applied to the transducer coil, the signal will be converted into a corresponding mechanical vibration of the transducer rod. The mechanical vibration is then transferred to the disk resonators which are coupled to each other by non-resonant coupling rods. Each disk resonator is a sharply resonant element and represents a series resonant circuit with a Q between 1,000 and 5,000. The disk resonators form a band-pass filter for the mechanical vibrations. Width of the pass band, which usually ranges from 500 cps to 35 kc, is determined by the type of metal and the area of the disk resonators. Bandwidth can also be varied by making the total area of the coupling rods larger or smaller, or by using more coupling rods. Because the disks are all identical, the bandwidth is not affected by the number of disks used; however, increasing the number of disks increases the skirt selectivity of the filter. That is, attenuation outside the pass band limits is increased.

e. Plate-type Electromechanical Filter (fig. 188.4). Longitudinal vibrations, set up in the input transducer plate by an input signal to the transducer coil, are transferred to a series of flat rectangular resonant plates. Each plate is resonant to the center frequency of the input signal and represents a series resonant circuit with a Q between 2,000 and 4,000. Bandwidth is not affected by the number of plates used; however, additional plates cause sharper cutoff outside the pass band limits. Operation and characteristics of the plate-type mechanical resonator are similar to those of the disk-type mechanical resonator (*d* above).

f. Neck-Coupled Electromechanical Filter. Illustrated in figure 188.4 is a neck-coupled torsional-type filter with eight resonant sections. Each large cylindrical section is a resonator tuned to the center pass band frequency of the filter. The resonators are coupled by smaller diameter necks. A slug at each end, securely clamped to a supporting frame, supports the entire assembly.

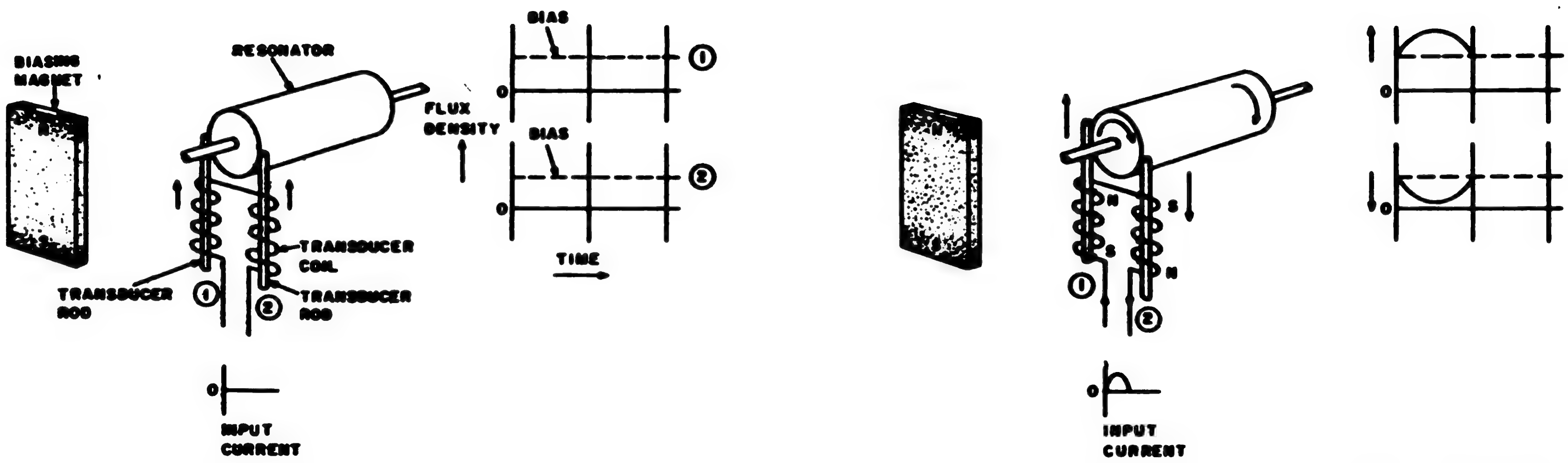
g. Operating Principle of a Torsional-Type Input Transducer. Illustrated in figure 188.7 is a torsional-type input transducer. Ferrite magnetostrictive rods, contained within the transducer coil are spot-welded to opposite sides of the cylindrical resonator. The two coils are so wound that they produce opposite magnetic fields. These fields interact with the common magnetic field from the near-by permanent magnet. A push-pull action of the transducer rods takes place as the magnetic fields of the coils alternately change at a frequency determined by the input current. As the rods alternately become shorter and longer, the resonator twists first in one direction and then in the other. This twisting action or mechanical vibration is then coupled to each cylindrical resonator in turn.

(1) A permanent magnet, placed near the magnetostrictive rods (A, fig. 188.7), will exert a permanent force on the rods. Since the force on each rod is the same, a balanced torque condition exists and the resonator remains stationary.

(2) A positive input alternation of current through coil ① (B, fig. 188.7) produces a magnetic field that adds to the magnetic field of the biasing magnet. The resultant magnetic field forces the rod in the coil to lengthen. The same current flows through coil ②; however, since coil ② is wound to produce a magnetic field that opposes the magnetic field of the biasing magnet, the resultant magnetic field decreases and the rod in this coil shortens. A push-pull action of the rods results and the cylindrical resonator twists in the direction shown.

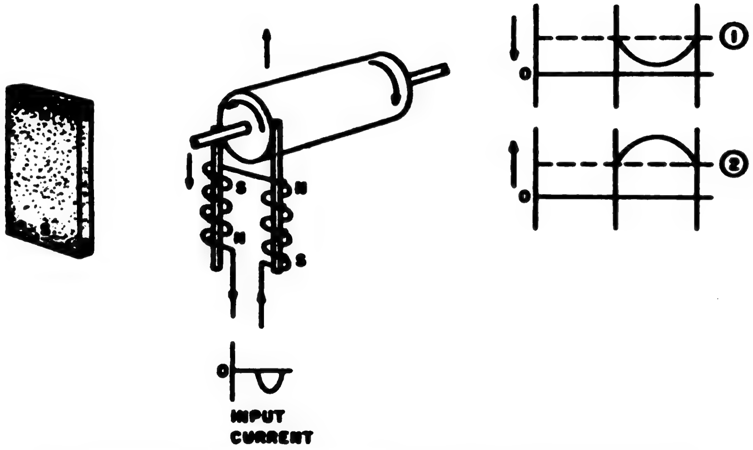
(3) A negative alternation of input current (C, fig. 188.7), will result in a push-pull action of the rods opposite to that shown in B, figure 188.7. The end of the resonator attached to the rods will twist in the direction shown while the other end of the resonator will continue to twist in the opposite direction because of the force applied by the initial push-pull action of the rods. Both ends of the same resonator are continuously out of phase.

h. Output Transducer. Mechanically and electrically, the output transducer is identical with the input transducer. However, their principles of operation are entirely different. The input transducer operates as a magnetostrictive de-



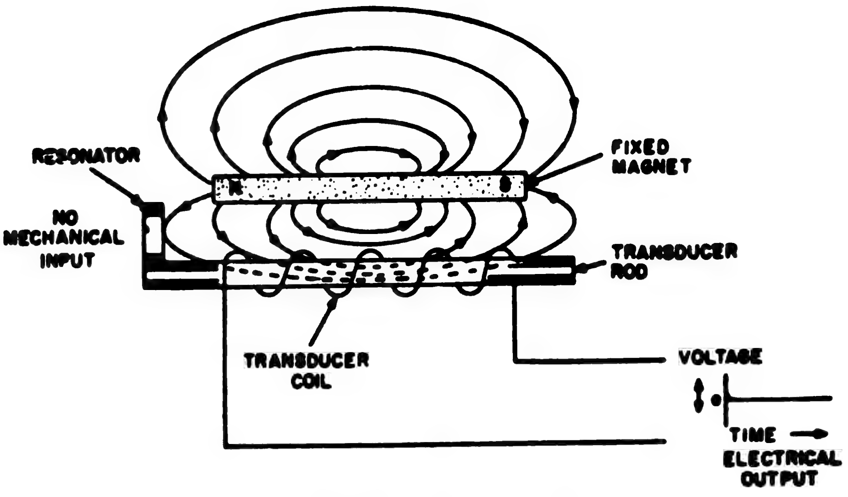
A. BALANCED TORQUE CONDITION WITH NO INPUT CURRENT

B. TORSIONAL FORCE DURING POSITIVE INPUT ALTERNATION

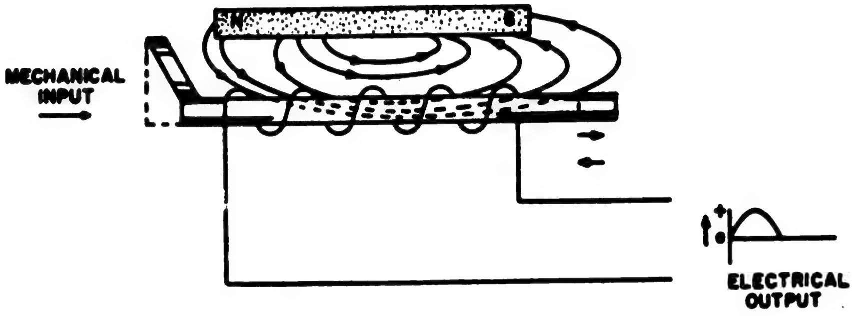


C. TORSIONAL FORCE DURING NEGATIVE INPUT ALTERNATION

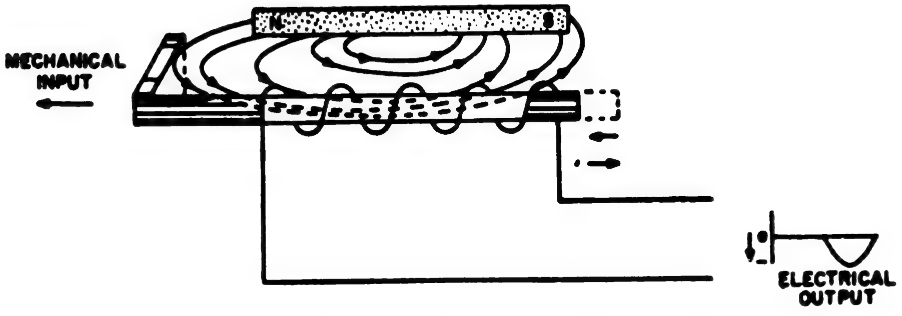
Figure 188.7. (Added) Typical operation of a torsional-type input transducer.



A. STATIONARY MAGNETIC FIELD



B. RIGHT-HAND MOVEMENT OF MAGNETIC FIELD



C. LEFT-HAND MOVEMENT OF MAGNETIC FIELD

TM665-C2-4

Figure 188.8. (Added) *Typical operation of an output transducer.*

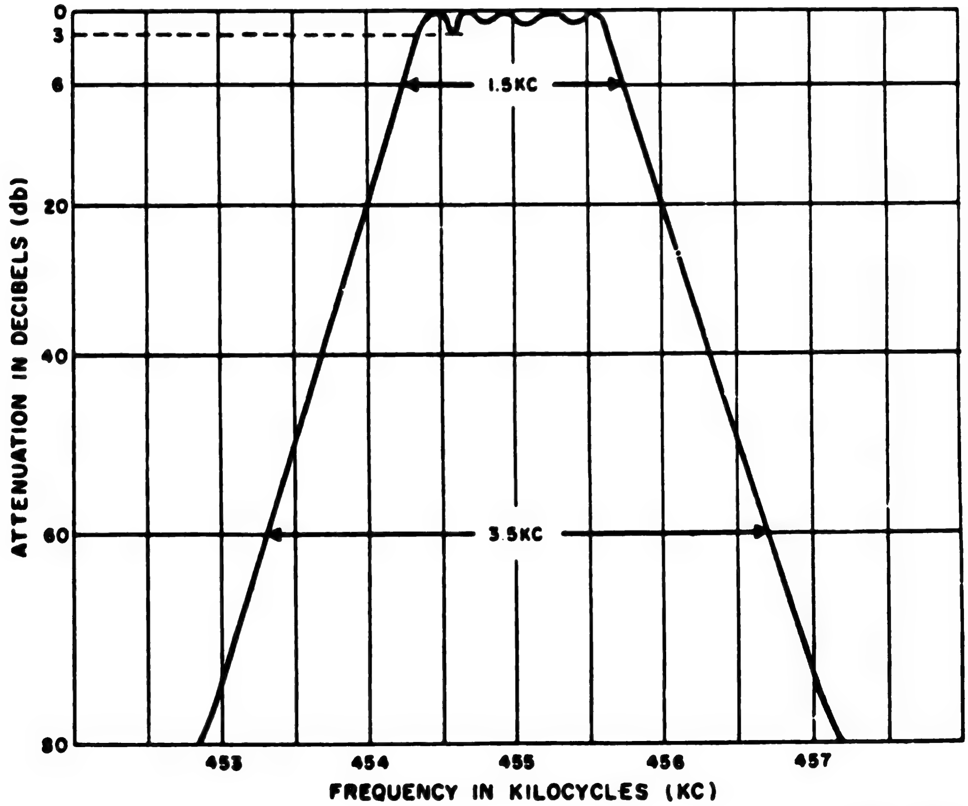
vice, and the output transducer operates as a small ac generator.

(1) Note that the transducer rod shown in A, figure 188.8, provides a low reluctance path for a number of lines of force between the north and south poles of the fixed magnet. Other lines of force cut the turns of the transducer coil. The rod and magnetic lines of force are stationary and no output voltage can be induced across the coil at this time.

(2) Movement of the rod (B and C, fig. 188.8), causes the magnetic field to move in unison with it and induces a voltage across the coil. As the displacement of the rod varies from its starting position to a maximum point on the right, then to a maximum point on the left, and back to its starting position, the magnetic field follows the movement of the rod. The resultant movement of the magnetic field induces a voltage and current in the coil that corresponds to the mechanical vibrations of the disk resonators.

(3) Output from the torsional-type transducer is obtained by the same basic principle as that described in (1) and (2) above.

i. Peak-to-Valley Ratio. Illustrated in figure 188.9 is a typical selectivity curve for an electromechanical filter. The curve has a pass band with steep skirts and a nearly flat top. These are the characteristics that make the filter so highly selective. The ripple across the top of the selectivity curve is an inherent characteristic of all electromechanical filters and appears as noise in the receiver output. The ratio of maximum to minimum ripple is called the peak-to-valley ratio. Production techniques and filter design are such that the peak-to-valley ratio can be made less than 3 decibels (db), thus minimizing the inherent noise output of the filter.



TM665-C2-5

Figure 188.9. **(Added)** *Typical selectivity curve for an electromechanical filter.*

j. Shape Factor. Shape factor or skirt selectivity is the ratio of bandwidth measured 60 db down from the 0-db point on the selectivity curve, to the bandwidth measured 6 db down from the 0-db point. For the selectivity curve illustrated in figure 188.9, a center frequency of 455 kc, a 3.5-kc bandwidth 60-db down, and a 1.5-kc bandwidth 6-db down are given. The shape factor of the filter represented by this selectivity curve is 3.5 to 1.5 or a ratio of 2.3 to 1. As the shape factor decreases (that is, as the ratio decreases), the attenuation of frequencies outside the pass band limits increases. In communication receivers, a filter with a low shape factor provides high rejection of adjacent-channel signals and the flat-top characteristic of the selectivity curve allows frequencies to pass that would normally be attenuated in a standard, rounded, if selectivity curve. Full benefit of the selectivity characteristics of the filter can be realized only when adequate shielding is provided between the external input and output circuits. If coupling takes place between the input and output circuits external to the filter, the selectivity characteristics will deteriorate.

k. Insertion Loss. Insertion loss is a power loss measured in db, resulting from the insertion of the electromechanical filter in a circuit. When a filter is inserted between an output impedance and an input impedance (as between two if stages in a receiver), the ratio of power in the output impedance when the filter is out of the circuit to the power in the output impedance when the filter is present determines the value of insertion loss. The insertion loss of an electromechanical filter is generally about 10 to 12 db. For applications requiring lower insertion losses, special filters can be produced with losses as low as 6 db.

l. Input and Output Impedances. Depending on its application, the filter may provide input and output impedances that are either high or low. When a filter is matched to circuits of high impedance, external capacitors must be connected in parallel with the transducer coils. This forms a high-impedance parallel-resonant circuit of 10,000 to 50,000 ohms, depending on the individual filter design. In practice, an external circuit source and load impedance of approximately 10 times the resonant input and output impedance of the filter is used. Filters can also be matched to circuits of low impedance, such as transistor circuits, by using a series-resonant input and output termination instead of the parallel-resonant condition. The lowest value of impedance that can be matched is determined by the stray capacity of the series-resonant circuit. In some types of filter, such as those used with balanced modulator circuits, each set of terminals on the filter is balanced to ground. This is a desirable feature when the filter is used in circuits of this type because the balanced-terminal condition eliminates the need for isolation transformers.

m. Multiple Resonances. As with many mechanical resonant circuits, elements of the filter have multiple resonances. These result in transmission of spurious frequencies through the filter. Proper design of the filter, however, places the spurious frequencies well outside the pass band area and thereby reduces them to a low level. In applications where increased attenuation of spurious frequencies is required, tuned circuits to provide additional selectivity precede or follow the filter.

141.2 Crystal Lattice Filters
(fig. 188.10)

a. General. Crystal lattice filters are usually composed of two to eight crystals in a lattice or bridge network. The filters operate within a narrow, well-defined band of frequencies usually ranging from 1 cycle to several hundred kilocycles. As a result, the crystal lattice filter, when used between the if stages of am, ssb, or fm receivers, will provide the same high selectivity performances as a multiple frequency conversion receiver. Bandwidth and selectivity characteristics of a receiver may be changed simply by switching in different filters having the desired characteristics. In addition to intermediate frequency application in receivers, the crystal lattice filter is also used in fire control, guided missile, and carrier telephone equipment.

Note. A detailed discussion of the fundamental properties of quartz crystals is given in paragraphs 40 through 43 and an analysis of basic crystal filter networks is given in paragraph 141*b*.

b. Lattice Networks. A typical lattice network configuration is illustrated in A, figure 188.12. Each arm of the network (Za1, Za2, Zb1, and Zb2) is a resonant circuit consisting

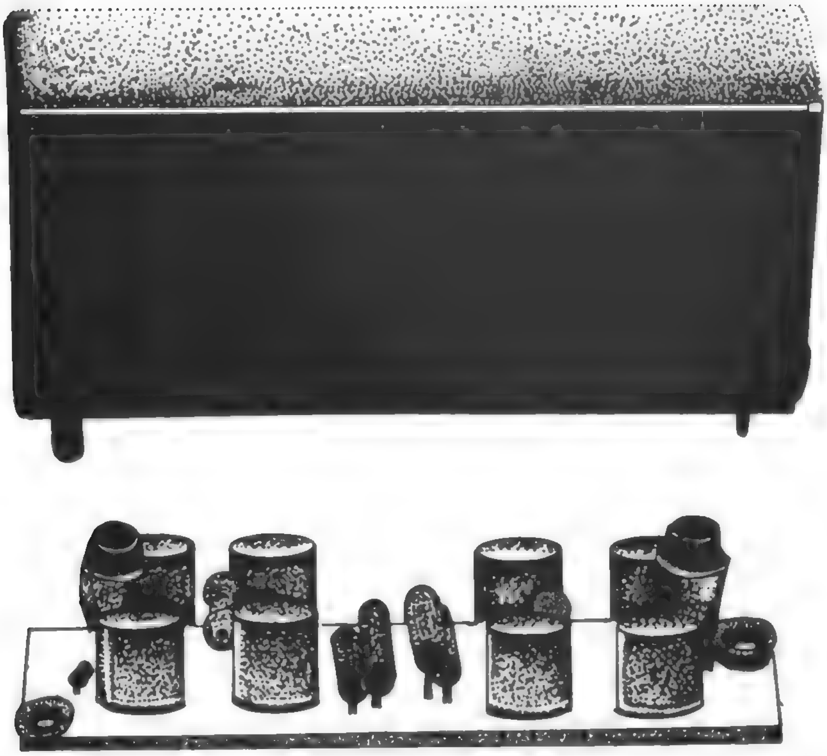


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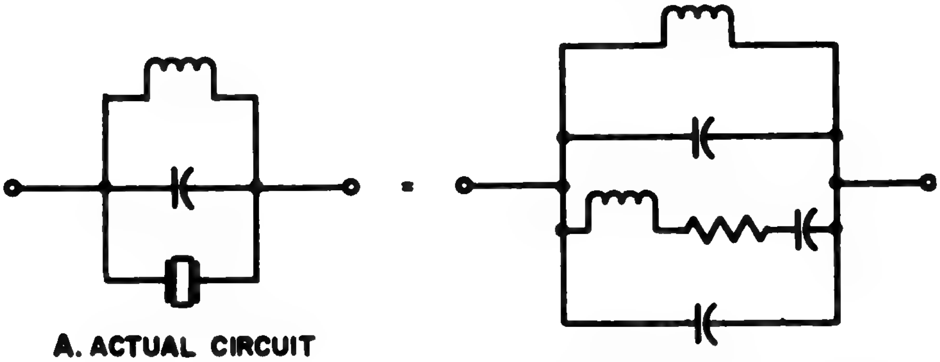
Figure 188.10. (Added) *Typical crystal lattice filter.*

of a quartz crystal and, in addition to the quartz crystal, may also contain an inductor and capacitor (fig. 188.11). The lattice network is designed so that the impedance value of Za1 is equal to Za2 and the impedance value of Zb1 is equal to Zb2. Impedance values of Za1 and Za2 may be similar or may differ from impedance values of Zb1 and Zb2 depending upon the application of the lattice network as a band rejection or bandpass filter. The typical configuration in A, figure 188.12 is redrawn as a bridge circuit in B to show that the lattice network is essentially a balanced symmetric bridge circuit. An input signal is applied to terminals 1 and 2 and the output signal is taken from terminals 3 and 4.



A. ACTUAL CIRCUIT

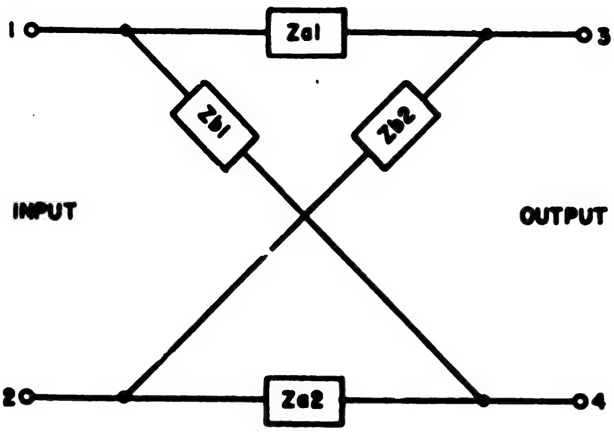
B. EQUIVALENT CIRCUIT

TM666-C2-11

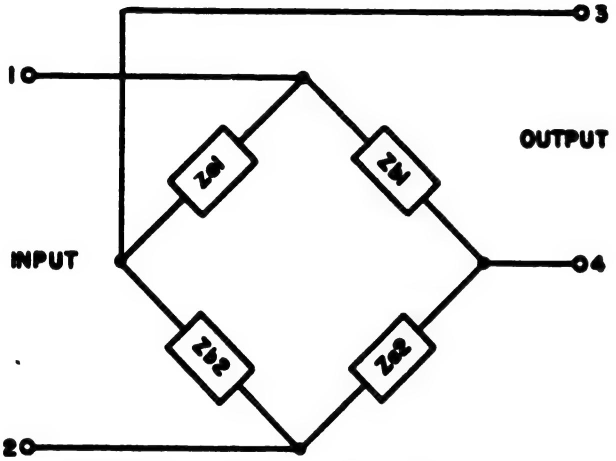
Figure 188.11. (Added) *Typical lattice-arm configuration.*

(1) *Band rejection filter*. For operation as a band rejection filter, the impedance value of the Za1 and Za2 arms must be equal to the impedance value of the Zb1 and Zb2 arms. In addition, the arms must be in phase and have a high impedance for the frequency that is to be attenuated. Under these conditions, the lattice network will have a high loss for the frequency that is to be attenuated and will function as a band rejection filter. For frequencies above and below the attenuated frequency, the arms of the lattice network will present either capacitive or inductive reactance, thus allowing these frequencies to pass. If the applied frequency causes the arms of Za1 and Za2 to offer an impedance opposite to the impedance offered by the arms of Zb1 and Zb2, the applied frequency will pass through the lattice network with minimum attenuation. In the design of a lattice network, the band rejection frequencies, upper and lower cutoff frequencies, and bandpass frequencies in a given band of frequencies, such as those that are normally present in the intermediate frequency stage of a receiver, may be positioned to different points by varying the impedance values of the Za and Zb arms.

(2) *Bandpass filter*. The lattice network filter may also be designed to permit a band of frequencies, known as the bandpass, to go through it with little or no loss, but attenuate all frequencies outside the bandpass. To function as a bandpass filter, the Za1 and Za2 arms are designed to have maximum attenuation for a given upper frequency within the band of applied frequencies, and the Zb1 and Zb2 arms are designed to have maximum attenuation for a given lower frequency within the same band of applied frequencies. These two attenuated frequencies are the upper and lower cutoff frequencies for the lattice network and provide the frequency limits of the bandpass.



A. TYPICAL CONFIGURATION



B. REDRAWN AS A BRIDGE CIRCUIT

TM665-C2-12

Figure 188.12. Typical lattice network.

(3) *Attenuation characteristics and bandwidth*. Figure 188.13 illustrates the attenuation characteristics and bandwidth for two types of crystal lattice filters (cw and voice). The bandpass

in each type, determined by the upper and lower frequency limits of the bandpass, is usually designed to be about 0.02 to 14 percent of the filter center frequency. In addition, the frequency difference between the upper frequency limit and the center frequency of the bandpass is the same as the frequency difference between the lower frequency limit and the center frequency of the bandpass. Attenuation characteristics and bandwith, for the filter used for cw reception in a receiver shows that it is a narrow band filter and provides very high selectivity. Several filters may be cascaded or several crystals may be connected in parallel in any lattice arm to provide greater selectivity than that obtainable with a single filter. The other type of filter (for voice reception) has the necessary wider bandwidth for voice reception. To obtain the wider bandwith, inductors are usually placed either in series or in parallel with each crystal.

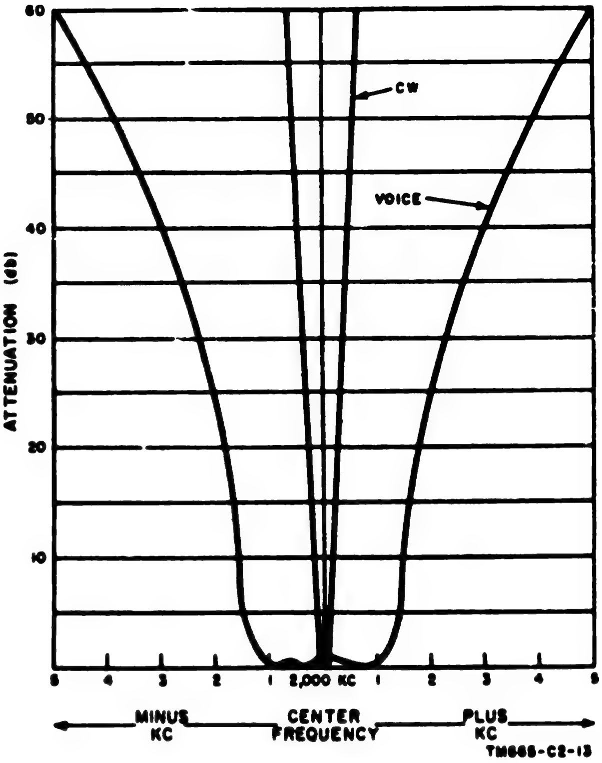


Figure 188.13. Attenuation characteristics and bandwidth for typical crystal lattice filters.

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DEPARTMENT OF THE ARMY TECHNICAL MANUAL

TM 11-665

C-W AND A-M RADIO TRANSMITTERS AND RECEIVERS

DEPARTMENT OF THE ARMY SEPTEMBER 1952

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2. REVIEW OF ELECTRICAL FUNDAMENTALS

Figure 1. Radio communication is used in all phases of military operation.

CHAPTER 1

INTRODUCTION

1. Communication by Radio

a. A good communication system is one of the prime requisites for a successful military operation. Because military aircraft and motor transport have increased the length of military lines, the importance of quick, reliable communication is vital. Tactical information must be disseminated immediately to widely separated places. The fastest, most useful, and versatile means of communication is radio. Many different types of radio equipment are used by the military services for specific purposes (fig. 1). Large fixed land radio installations providing communication over great distances include powerful radio transmitters and sensitive receivers. Small portable radio sets are used by troops in the field for short-distance communication. Specially constructed radio units are installed on aircraft to permit communication between planes or from planes to ground stations. Shipboard radio equipment enables a ship to keep in constant touch with other ships and land bases. The great advantage of a radio communication system is that no connecting wires are used between the point where the information originates and the point to which the information is sent. Instead, the connecting link takes the form of electromagnetic waves in space.

b. Modern radio has been developed by a large number of men, some of whom contributed basic ideas of theory and others practical circuits and devices. Outstanding among the early workers were such men as Faraday, Maxwell, Hertz, and Marconi. In 1896, Marconi succeeded in transmitting a signal over a distance of 2 miles with no connecting wires between the transmitting device and the receiving apparatus. *Wireless* communication was shown to be possible. Two years later, the range of the crude equipment was extended to approximately 30 miles. In the year 1899, a regular wireless telegraph service was established across the English Channel. Just 2 years later, Marconi's crude apparatus, located at Poldhu, Wales, sent out a signal which was picked up by a receiver at St. Johns, Newfoundland. The Atlantic Ocean had been spanned by a device which had been a mere laboratory curiosity. From this early equipment, modern radio communication has emerged.

2. Electrical Background

a. Electrical circuits and principles form the basis of operation of a radio system. To understand radio, it is necessary to be familiar with electrical fundamentals, which are reviewed in chapter 2.

b. Electricity may be classified as *power electricity* in which the primary concern is to transmit electrical *power* efficiently, and *communications electricity*, in which the main concern is to transmit *intelligence* efficiently. Intelligence in this sense is broadly defined as anything that conveys information. It may be in the form of telegraphic code, speech, music, or pictures. In the study of communications electricity, very small amounts of power usually are considered. Although the output power from large fixed ground transmitters can be appreciable, the actual received power at some remote location usually is measured in milliwatts, microwatts, or, frequently, even in micromicrowatts. The output power of field transmitters usually does not exceed several hundred watts, and a small portable unit may radiate only a fraction of a watt of power. The output delivered by most receivers rarely exceeds several watts and, if headphones are used, the output power is considerably less.

3. Frequencies Used

a. Speech and music fall within the a-f (audio-frequency) range. We hear audio frequencies because our ear drums vibrate at a frequency that corresponds to the frequency of the sound. The average human ear responds to frequencies from about 16 cps (cycles per second) to about 16,000 cps. Deep bass tones produced by a pipe organ, for example, may have a frequency which extends down to the lower limit of this range. The sound waves produced by a shrill high-pitched whistle may have a frequency of 15,000 cps or even higher. The most important frequencies used in human speech range from about 200 to 2,500 cps. Compared with radio frequencies, which extend from approximately 20 kc (kilocycles) to well over 3,000 mc (megacycles), these audio frequencies are low.

b. It is not possible to radiate audio-frequency power efficiently nor to span great distances with these low frequencies. Several hundred watts of audio-frequency power, radiated by large loudspeakers may span a distance of only a few miles. If this method were used to transmit audio intelligence, it would be useful for only short distances and when the level of outside noises or sounds does not obscure the information conveyed. In addition to these limitations, selectivity of information is not possible. All persons within hearing range would receive the information and the listener could not tune his *receiver* to a different band or frequency. Therefore, only one channel would be available and the utility of radio communications would be limited.

c. None of the these limitations apply when a radio-frequency signal is used to *carry* the intelligence. Tremendous distances can be covered; many channels, each carrying information, can be used; and selectivity of information is possible. Superimposing audio-frequency intelligence on a radio-frequency carrier wave involves a process called *modulation*. One type of modulation, called a-m (amplitude modulation), requires that the *amplitude* of the carrier wave be varied in accordance with the intelligence.

d. Radio frequencies extend over a wide range. In a certain radio transmitter used today the operating frequency is 22 kc. Another radio equipment produces a radio-frequency output of 28,000 mc. The characteristics and circuits used at different radio frequencies vary widely, depending on the specific frequency used. For convenience, groups or *bands* of radio frequencies have been set up. The accompanying chart shows some of these bands that are used for military purposes. The characteristics indicated are very general and the chart gives only an over-all picture.

Band	Frequency range	Distance range	
		Day	Night
vlf (very low frequency).	Below 30 kc		
lf (low frequency)	30 to 300 kc	Long	Long.
mf (medium frequency.	300 to 3,000 kc	Medium	Long.
hf (high frequency)	3 to 30 mc:		
	3 to 10 mc	Short to medium.	Medium to long.
	10 to 30 mc	Long	Long.
vhf (very high frequency).	30 to 300 mc	Short	Short.
uhf (ultrahigh frequency).	300 to 3,000 mc	Short	Short.
shf (superhigh frequency).	3,000 to 30,000 mc	Short	Short.

e. The velocity of electromagnetic radio energy in space is the same as the velocity of light—that is, 300,000,000 meters per second or 186,000 miles per second. For most practical purposes, this velocity is constant regardless of the frequency used or the conditions of transmission. The length of the radio wave is the distance traveled by the wave in the period of time required to complete 1 cycle. To find the wavelength when the frequency is known, it is necessary to divide that frequency into the velocity given above as follows:

$$\text{Wavelength (in meters)} = \frac{300{,}000{,}000 \text{ (velocity in meters per second)}}{\text{frequency (in cycles per second)}}$$

To find the frequency when the wavelength is known, it is necessary only to divide that wavelength into the velocity given above as follows:

$$\text{Frequency (in cycles per second)} = \frac{300{,}000{,}000 \text{ (velocity in meters per second)}}{\text{wavelength (in meters)}}$$

4. Components of Radio Communication System

a. In the basic radio communication system shown in block form in figure 2, a radio transmitter is used to generate the r-f (radio-frequency) waves which are to be radiated into space. This transmitter may contain only a simple oscillator stage. Usually, the output of the oscillator is applied to a power amplifier which allows greater stability to be incorporated into

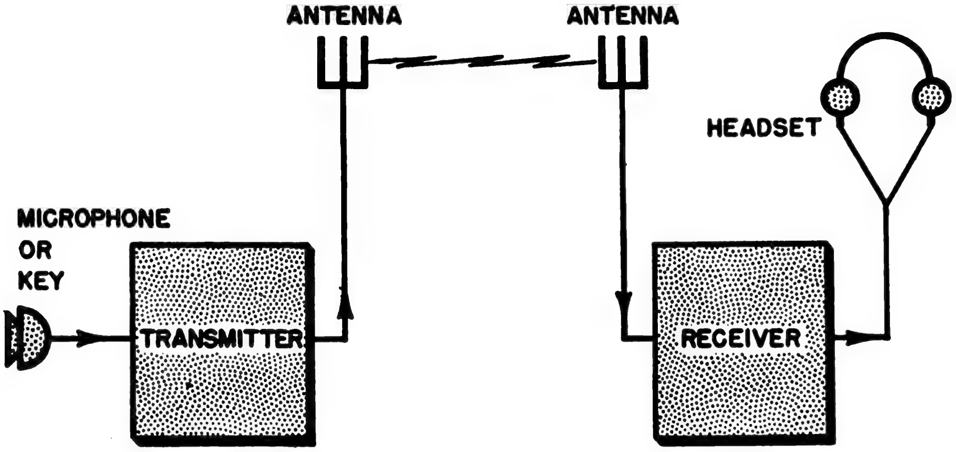

Figure 2. Block diagram of basic radio communication system.

oscillator circuity and further allows great increases in transmitter output power. Power amplifiers and coupling circuits are discussed in chapter 4.

b. A telegraph key may be used to control the energy waves produced by the transmitter. When the key is closed, the transmitter produces its maximum output. When the key is opened, no output is produced. In this way, a message in telegraphic code can be transmitted.

c. If speech intelligence is to be transmitted, a microphone is used to convert the sound energy produced by the transmitter into electrical energy. A speech amplifier and a modulator must now be included in the transmitter. The modulator superimposes the a-f speech intelligence on the r-f carrier wave.

d. The output of the transmitter is applied to the transmitting antenna, which radiates the energy into space in the form of electromagnetic waves. A small portion of the radiated energy then is picked up by a receiving antenna, and the received energy is applied to the radio receiver.

e. The receiver selects the desired transmitted signal, amplifies the received signal, and separates the audio intelligence from the radio-frequency carrier. Many different receiver circuits can be used to accomplish this. The output of the radio receiver is applied to a reproducer, usually a loudspeaker or a headset, which converts the audio-frequency electrical energy into sound energy.

5. Summary

a. The effectiveness of a communication system often determines the success or failure of a military operation.

b. In order to understand the principles of operation of radio transmitters and receivers, a background in electrical fundamentals is essential.

c. One method of superimposing a-f intelligence on an r-f carrier is to vary the amplitude of the carrier in accordance with the intelligence. This is known as amplitude modulation.

d. The velocity of electromagnetic energy in space is constant. If the frequency of radio energy is divided into the velocity, the wavelength is obtained. If the wavelength is divided into the velocity, the frequency is obtained.

e. A basic radio communication system is composed of transmitter, key or microphone, transmitting antenna, receiving antenna, receiver, and reproducer.

6. Review Questions

a. Give several advantages of a radio communication system compared with other communication systems.

b. Why is it necessary to superimpose the audio intelligence on a radio-frequency carrier wave?

c. Calculate the wavelength which corresponds to the following electrical frequencies: 60 cps, 1,000 cps, 1,000 kc, and 1,000 mc.

d. What are the main components of a basic radio communication system?

CHAPTER 2

REVIEW OF ELECTRICAL FUNDAMENTALS

Section I. SOURCES OF ELECTRICITY

7. Mechanical Source

a. The applications of electricity are based on two related invisible forces known as *electric* and *magnetic* forces. The mechanical generation of electricity depends on the principle of magnetic force. Any conductor, straight or coiled, through which an electric current is flowing has a magnetic force around it and at right angles to it (fig. 3).

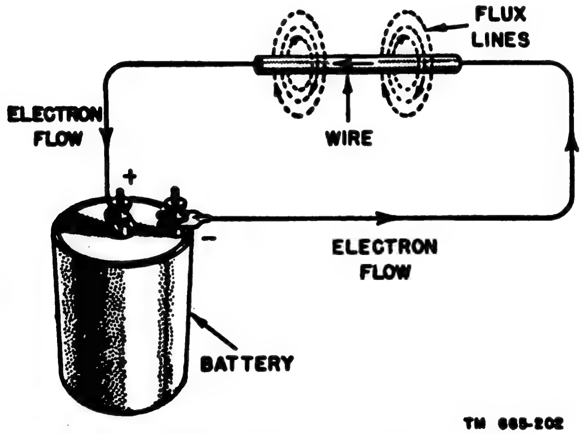

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Figure 3. Magnetic field around conductor.

The strength and the direction of this magnetic force at any point in the vicinity of the conductor are indicated by the magnetic *field*, which in theory is present throughout all space. Practically, it becomes negligibly weak at a relatively short distance from the current-carrying conductor. This invisible field of magnetic force is represented by imaginary *lines of force* or *flux lines* that show, by the direction in which they lie, the direction in which the magnetic force is acting. A magnetic object inserted into the field moves in the direction indicated by the lines of force. In the case of a straight current-carrying conductor, the lines of force are circles concentric with the conductor, and their direction is related to the direction of electron flow through the conductor as indicated by the arrows in figure 3. The *number* of lines of force in a chosen cross section of the field is a measure of the strength or *intensity* of the magnetic force. The number of flux lines per square inch, or per square centimeter, is called the *flux density*.

b. Just as current flowing in a conductor produces a magnetic field around it, the converse of this is also true. When a conductor is moved across a magnetic field so that it cuts across the lines of magnetic force, an electromotive force or voltage is generated across its terminals. If the circuit is completed, current flows through it. An electric generator (fig. 4) changes mechanical energy into electrical energy by utilizing this principle. In its simplest form an electric generator consists of a single loop of wire, called an *armature*, which is mounted on a shaft that can be rotated through the magnetic field extending between the poles of a permanent magnet or an electromagnet.

c. When the armature is turned counterclockwise from the horizontal position shown as a solid line in figure 4, the two long sides of the lop move past the pole pieces and cut the magnetic flux lines perpendicularly. As the right-hand half of the loop cuts upward through the lines of force, a voltage is induced in it in one direction. At the same time, the left-hand half of the loop cuts downward through the lines of force, and has a voltage induced in it of opposite polarity. The voltages induced in the halves of the loop are additive, and the total generated voltage can be measured at the ends of the loop. If the loop terminals are closed through an external circuit, the electron flow is in the direction indicated by the arrows (fig. 4).

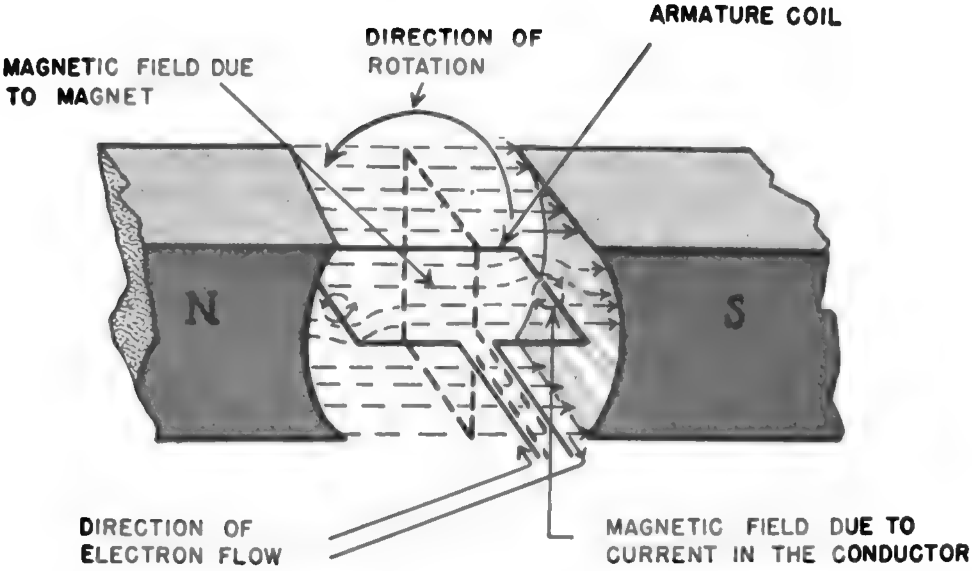

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Figure 4. Simple electric generator.

d. As the armature is rotated to the position shown as a broken line in figure 4, the two long sides of the loop move parallel with the lines of force. They do not cut any flux lines and consequently no voltage is induced in the loop in this position. As the armature is rotated still further in a counterclockwise direction, the two halves of the loop interchange their positions. As a result, voltages are now induced in directions opposite to those previously described, and the electron flow also reverses. Thus, the induced voltage reaches a maximum value twice during one complete armature rotation, when the loop is cutting the field at right angles, and drops to zero for the two positions when the loop is moving parallel to the magnetic field.

e. In the simple generator just described, a-c (alternating-current) voltage is generated. This voltage is made available to an external circuit by means of two *slip rings* (A of fig. 5), which are connected to the open ends of the armature coil. These slip rings make continuous contact with two

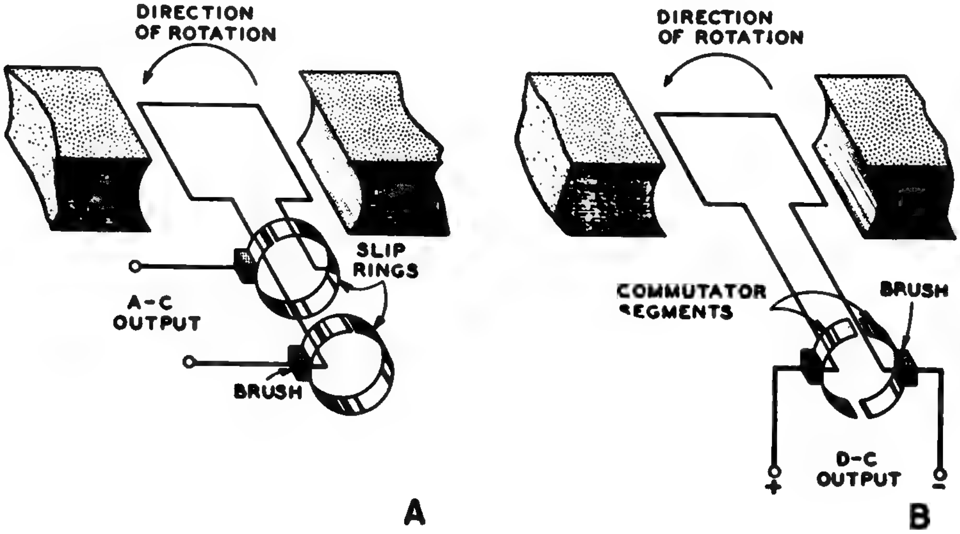

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Figure 5. Taking power from simple electric generator.

fixed brushes as they rotate. In a d-c (direct-current) generator, the voltages are produced in the same way as in an a-c generator. However, d-c output is obtained, as in B, by a switching arrangement on the rotating shaft known as a *commutator*. A basic commutator consists of two separate metallic elements insulated from each other, and each connected to one terminal of the loop. At the precise moment when the induced voltages reverse their direction, the connections of the commutator segments to the external circuit also reverse, so that the output terminals of the generator always have the same polarity. As a result, a unidirectional current (d-c) is produced.

8. Chemical Source

a. When two dissimilar materials are inserted into an acid or alkaline solution, called an *electrolyte*, a voltage is found to exist between them. The magnitude of this voltage depends on the substances used. Frequent combinations are copper and zinc, zinc and carbon, and cadmium and mercury. One type of *primary cell* (fig. 6) consists of two metal plates, one copper and the other zinc, acted upon chemically by a dilute solution of sulphuric acid. If an external circuit consisting of resistor *R* is provided between the two plates, called *electrodes*, the voltage causes an electron flow from copper to zinc inside the electrolyte and from zinc to copper through the external circuit. This electron flow is capable of doing work. Sometimes the electrolyte is in the form of a paste. The ordinary *dry cell*, for instance, uses ammonium chloride paste as the electrolyte, and provides an output of 1.5 volts. Other electrolytes and electrodes provide voltages varying from about .7 to 2.5 volts. If the electron flow in a primary cell continues for some time, the cell becomes exhausted, since one of the electrodes is literally eaten away by the electrochemical process. The active elements must then be renewed or the cell discarded.

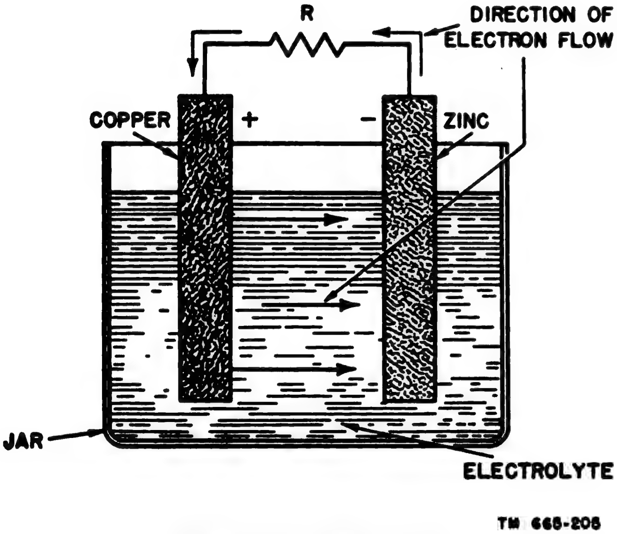


Figure 6. Primary cell.

b. Some cells, known as *secondary cells* or *storage batteries*, permit their chemical processes to be reversed; they can be recharged by supplying current to them from an outside source. During charging, electrical energy is transformed and stored in the form of chemical energy. During discharge, this stored energy again is liberated in electrical form to do useful work. Common types of secondary cells are the *lead-acid cell* and the *Edison cell*. In the charged lead cell, the positive electrode is made of lead peroxide, the negative electrode of spongy lead, and the electrolyte consists of a dilute solution of sulphuric acid. During discharge, both plates of the cell become coated with lead sulphate and the electrolyte becomes more diluted, because of the formation of water. The cell is restored to its original (charged) condition by passing current through it in the opposite direction. This cell provides a voltage of about 2.1 volts. The Edison storage cell uses nickel hydrate as the positive active material and iron oxide as the negative active material in an electrolyte consisting of a 21-percent solution of potassium hydroxide, mixed with a small amount of lithium hydrate. Its voltage is 1.3 volts. The Edison cell stands rough usage better than the lead cell and has a larger storage capacity in proportion to its weight.

9. Piezoelectric Source

Some crystals have the property of generating an emf (electromotive force) when subjected to mechanical strain (compressed or expanded). Quartz and Rochelle salt crystals are materials that produce this effect, and the electricity produced is called *piezoelectricity* (pressure electricity). This property of crystals is extremely useful. In addition, the action is reversible; that is, when a voltage is impressed on a crystal it changes its shape and therefore can be made to oscillate; consequently, it can be used as parts of oscillator circuits in transmitters to provide remarkable frequency stability. Crystals are used also in filter circuits of receivers because they are equivalent to a very sharply tuned circuit.

10. Photoelectric Source

Some metals emit electrons when exposed to radiations in the visible, infrared, and ultraviolet portions of the spectrum. An example of a light-sensitive surface is a silver base upon which is evaporated a thin layer of cesium oxide. The greater the illumination by the radiation the more electrons are emitted, and thus more photoelectric current flows. Electricity generated in this way is called *photoelectricity.*

11. Thermoelectric Source

If the junction point of two dissimilar metals is heated, an electromotive force is produced. A current flows if the circuit is closed by connecting the open ends of the metals to each other or to an external circuit. Within limits, the greater the heat applied to the junction, the greater is the voltage generated. Electricity generated in this way is called *thermoelectricity.* If an electric current is made to flow through the junction of two different metals, heat proportional to the current flow is produced at the junction point, causing a voltage to be generated. A pair of metals frequently used to form such a thermoelectric junction, or *thermocouple,* is copper and the alloy constantan. In radio equipment, thermocouples generally are used in meters that measure r-f currents.

Section II. DIRECT CURRENT

12. Simple D-C Circuit

The simplest form of a direct-current electric circuit is a battery with a resistor connected to its terminals (fig. 7). The resistor represents any external apparatus or *load* connected to the voltage source. A complete d-c circuit has an unbroken path for the current flow from the battery, through the load, and back into the battery. The amount of current flow through the circuit, the applied voltage, and the resistance are subject to an important relationship between them, known as *Ohm's law.*

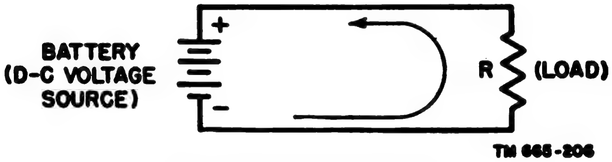


Figure 7. Simple circuit.

a. Ohm's Law. The current flowing in an electrical circuit is directly proportional to the applied voltage and inversely proportional to the resistance of the circuit. In equation form, it is

$$I \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}$$

This equation gives the value of current in a circuit when its resistance and the applied voltage are known. When the current in amperes and the resistance in ohms are known, the applied voltage is

$$E = I \times R$$

If the voltage acting in the circuit and its current are known, the resistance of the circuit is

$$R = \frac{E}{I}$$

All three forms of Ohm's law are used frequently in electronics. In complicated circuits with many branches, Ohm's law alone is often insufficient to determine the distribution of currents and voltages, and other methods must be used. One method is provided by *Kirchhoff's laws.*

b. Kirchhoff's Laws (fig. 8). In any circuit the following two laws apply:

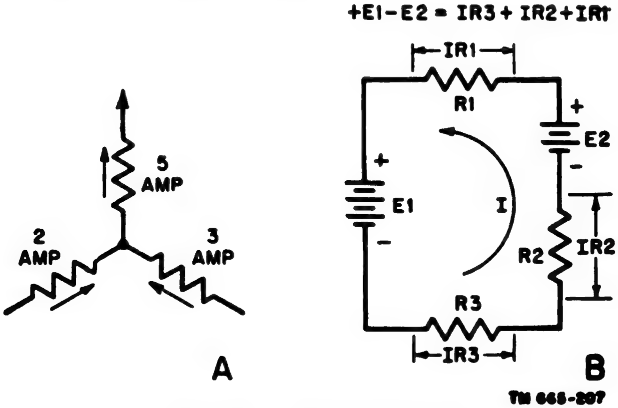


Figure 8. Kirchhoff's laws.

(1) At any point in the circuit the sum of the currents flowing toward the point is equal, as in A, to the sum of the currents flowing away from it.

(2) In any closed loop, the algebraic sum of the voltage drops around the circuit (including the source) is equal to zero. To apply the second law, algebraic signs (+ or −) are given to all voltages and currents. In following any closed loop in a certain direction, clockwise or counterclockwise, all voltages which tend to produce currents in the chosen direction are taken as positive, and a negative sign is given to all opposing voltages and currents, as in B. A series of equations then may be written for each of the closed loops, and these, together with the application of the first law, will solve the circuit problem.

13. Series Circuit

Very few electrical circuits are as simple as that shown in figure 7, which contains only a single resistance element. The methods of connecting more than one resistor in an electric circuit are *series*, *parallel*, and *series-parallel*. In the series circuit (fig. 9), the current flows from the source of voltage, in the direction of the arrows, through the first resistor, $R1$, then through the second and third resistors, $R2$ and $R3$, respectively, and finally back to the source. The current is given by Ohm's law and has the same value everywhere in the circuit. The voltage drops across each of the resistors are the product of current and resistance and can therefore all be different. The total resistance of a series circuit is the sum of the individual resistances. Numbering the resistors $R1$, $R2$, $R3$, and so forth, the total resistance

$$R\ (\text{total}) = R1 + R2 + R3 + R4 + \ldots R_n$$

where the dots represent any additional resistors used. Therefore,

$$E\ (\text{total}) = E1 + E2 + E3 + E4 + \ldots E_n$$

Example: Assume that the voltage in figure 9 is 300 volts, $R1$ is 5,000 ohms, $R2$ is 22,000 ohms, and $R3$ is 3,000 ohms. The total resistance then is R (total) $= R1 + R2 + R3 = 5{,}000 + 22{,}000 + 3{,}000 = 30{,}000$ ohms. By Ohm's law, the current flowing in this circuit is

$$I = \frac{E}{R} = \frac{300}{30{,}000} = .01 \text{ ampere} = 10 \text{ ma (milliamperes)}$$

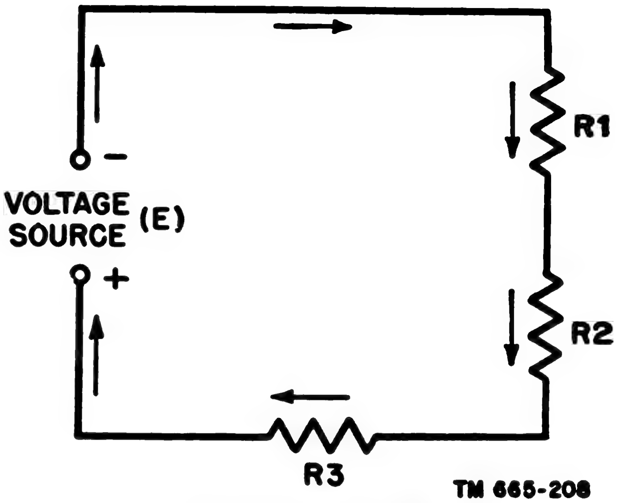


Figure 9. Series circuit.

14. Parallel Circuit

a. In the typical parallel circuit (fig. 10), the current flows from the voltage source, E, in the direction indicated by the arrows, to a common connection point at the top of the three resistors $R1$, $R2$, and $R3$. At the lower connection point the three currents again combine, adding up to the same current that flowed into the upper junction. The voltage drop across each branch, which is the product of the branch current times the branch resistance, is equal to the voltage of the source. The individual currents through resistors $R1$, $R2$, and $R3$ are equal to $E/R1$, $E/R2$, and $E/R3$, respectively, in accordance with Ohm's law. The branch currents, therefore, can all be different in a parallel circuit, and the voltage drops across the resistors are all equal.

b. The total resistance of a parallel circuit is always *less* than the *lowest* value of resistance present. That this is so follows from Ohm's law, since the voltage is fixed and the total current must be greater than the current through any branch

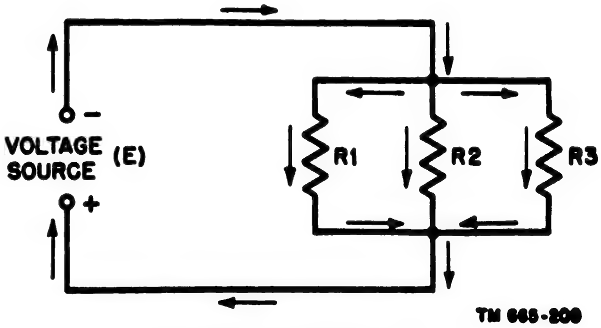


Figure 10. Parallel circuit.

resistor. The total resistance of a number of resistors in parallel is given by

$$R=\frac{1}{\frac{1}{R1}+\frac{1}{R2}+\frac{1}{R3}+\frac{1}{R4}+\cdots\frac{1}{R_n}}$$

For only two resistors in parallel the formula is

$$R=\frac{R1\times R2}{R1+R2}$$

Example: Assume that the voltage in figure 10 is 250 volts, $R1$ is 10,000 ohms, $R2$ is 5,000 ohms, and $R3$ is 4,000 ohms. The total resistance then is

$$R\text{ (total)}=\frac{1}{1/10{,}000+1/5{,}000+1/4{,}000}=1{,}818\text{ ohms}$$

The total current in the circuit is

$$I\text{ (total)}=\frac{E}{R\text{(total)}}=\frac{250}{1{,}818}=.1375\text{ ampere}=137.5\text{ ma}$$

The current in each branch can be found by application of Ohm's law. The current through $R1$ is

$$E/R1=\frac{250}{10{,}000}=.025\text{ ampere or 25 ma}$$

the current through $R2$ is

$$\frac{250}{5{,}000}=.05\text{ ampere or 50 ma}$$

and the current through $R3$ is

$$\frac{250}{4{,}000}=.0625\text{ ampere or 62.5 ma}$$

As a check, the sum of the three branch currents equals

$$25+50+62.5=137.5\text{ ma}$$

or the same as the total current calculated before.

15. Series-Parallel Circuit

An electrical circuit can have resistors both in series and in parallel, as illustrated in *A* of figure 11. A circuit of this type can be handled, as in *B*, by this general rule: Reduce the parallel resistances first and then the series resistances in different parts of the circuit to equivalent resistances that can be handled as single resistances in either a simple series or a simple parallel circuit.

Example: Let the voltage source of figure 11 be 250 volts, let $R1=5{,}000$ ohms, $R2=20{,}000$ ohms, and $R3=8{,}000$ ohms. First find the equivalent resistance, R_e, of $R2$ and $R3$ in parallel. By the formula given above

$$R_e=\frac{R2\times R3}{R2+R3}=\frac{20{,}000\times 8{,}000}{20{,}000+8{,}000}=5{,}714\text{ ohms.}$$

The total resistance of the simple series circuit is then

$$R1+R_e=5{,}000+5{,}714=10{,}714\text{ ohms,}$$

and the total current is

$$I=\frac{E}{R}=\frac{250}{10{,}714}=.023\text{ ampere}=23\text{ ma}$$

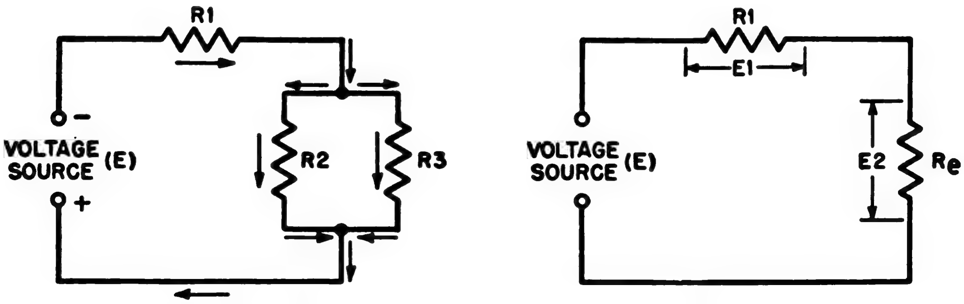
The voltage drop across R_e is then

$$E2=I\times R_e=.023\times 5{,}714=131\text{ volts}$$

and the branch currents are found as in any other parallel circuit with a voltage of 131 volts.

16. D-C Voltage Divider

A voltage divider taps the voltages required for the proper operation of electronic tubes in radio transmitters and receivers from a common power supply. For the simple divider shown in figure 12, the method of calculating the resistances is as follows: Assume that the supply voltage, *E*, and



SERIES-PARALLEL CIRCUIT
A

EQUIVALENT SERIES CIRCUIT
B

Figure 11. Series parallel circuit.

the tapped voltages, $E1$ and $E2$, and currents $I1$, $I3$, and $I4$, are known. The return circuit for $I1$ and $I3$ is to the positive side of the voltage source. It is required to find the values of $R1$, $R2$, $R3$, I, and $I2$. By applying Kirchhoff's first law, the current flowing to the junction, A, must equal the current flowing away from that junction. Therefore

$$I = I1 + I2$$

and

$$I2 = I3 + I4 \text{ at junction B}$$

According to the second equation, current $I2$ can be found by simply adding $I3$ and $I4$, both of which are known. When this value for $I2$ is substituted in the first equation, the value of I can be found. Since all currents and voltages are known, the values of $R1$, $R2$, and $R3$ can be calculated by Ohm's law as follows,

$$R1 = \frac{(E - E1)}{I}$$

Also

$$R2 = \frac{(E1 - E2)}{I2}$$

and

$$R3 = \frac{E2}{I4}$$

A similar procedure is followed for more complicated dividers.

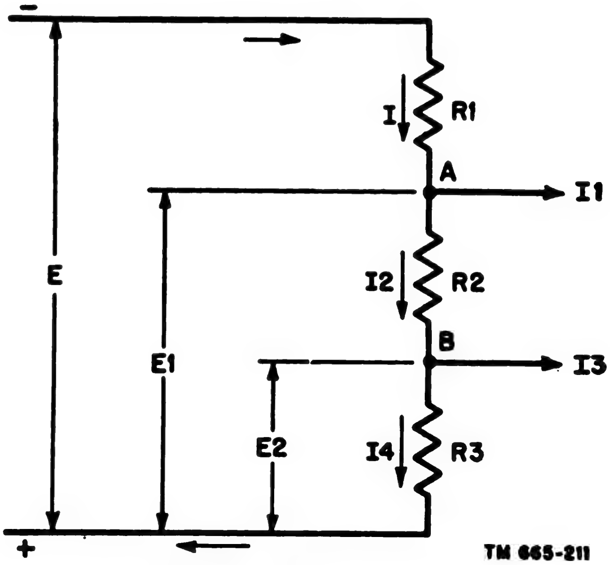


Figure 12. D-c voltage divider.

Section III. ALTERNATING CURRENT

17. Generating Alternating Current

It has been shown that a simple a-c generator produces its voltage in the form of a rising and falling wave. During one complete rotation, or 360°, the loop generates 1 *cycle* of a-c voltage. The number of cycles completed in 1 second is called the *frequency*, and it is directly determined by the speed of rotation of the generator loop. A rapid rotation produces a high frequency, and a slow rotation results in a low frequency.

a. Sine Curve.

(1) The rising and falling characteristics of the voltage in the simple a-c generator can be plotted throughout 1 cycle from 0° to 360°, and the resulting curve is called a *sine curve*. It is important to understand the relationship between the sine curve and a circle. Assume that the maximum value, E, of the alternating voltage of an a-c generator is represented by the length of the radius of a circle and is equal to 1 (fig. 13), and that this radius rotates counterclockwise in the circle, as does the actual wire loop in an a-c generator. A line drawn from the end of the rotating radius perpendicular to the horizontal diameter of the circle is known as the *vertical projection* of the radius. As the radius rotates, its vertical projection, as shown, varies between $+E$ and $-E$—in this case between $+1$ and -1. If the value of this projection is plotted against the counterclockwise angle that the radius makes with the horizontal diameter, a sine curve is produced, and the vertical projection at any point is equal to the sine of the angle.

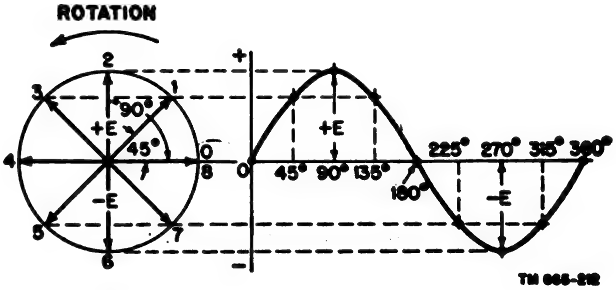


Figure 13. Generation of sine wave.

(2) Assume that the horizontal starting position, 0, of the rotating radius corresponds to the vertical position of the wire loop (broken line, fig. 4) in the simple a-c generator previously discussed. In this position, the loop is moving parallel to the magnetic lines of force and therefore no voltage is generated. In position 1 (fig. 13), the radius has rotated counterclockwise through 45° and the magnitude of the voltage generated is represented by the vertical projection of the rotating radius above the 45° marker in the sine-wave curve. In position 2, the radius has rotated through an angle of 90°, and the vertical projection at this point represents the maximum generated voltage, $+E$. This corresponds to the horizontal position of the loop (solid line, fig. 4) in the a-c generator when it is moving at right angles to the lines of magnetic flux. In position 3, the radius has rotated through 135°, the vertical projection is the same as in position 1, and the voltage falls back to the value it had in position 1. The voltage falls back to 0 in position 4, when the rotating radius as well as the actual wire loop has rotated through 180°. Since a full cycle consists of a rotation of 360°, one-half cycle has been completed at this point. All of this half-cycle is on the positive side of the axis.

(3) In position 5, corresponding to a rotation of 225°, the generator voltage again has started to rise, but now in the opposite direction. This is indicated by the negative vertical projection of the rotating radius at 225°. The remainder of the negative half-cycle is generated in a manner similar to that described above. If the wire loop and its rotating radius representation continue to revolve, further sine wave voltage cycles are traced out. In figure 13, the degrees measured along the sine wave axis are known as *electrical degrees*, or the *relative phase* of the a-c voltage. The maximum values of voltages $+E$ and $-E$, at 90° and 270° respectively, are called the *amplitude* or peak of the sine wave.

b. Phase Angle or Phase Difference.

(1) *Phase angle* or *phase difference* denotes a specific time interval between two or more periodic quantities alternating at the *same frequency*, such as between two voltages, two currents, or between a voltage and a current. Since each a-c cycle requires exactly the same amount of time, the phase difference is expressed conveniently in fractions of a cycle or electrical degrees, *time* being implied in either case. Two a-c quantities are said to be *out of phase*, or have a phase difference, if one of the quantities always begins its cycle before the other. The quantity which starts and ends its cycle before the other is said to *lead* the second quantity by a certain phase angle; the second quantity can be said to *lag* the former by the same phase angle.

(2) Phase differences between alternating quantities are measured at corresponding parts of their cycles, as shown for the two sine waves in figure 14. In A, curve 1 has a value of 0 at the 0° reference point, whereas curve 2 is at its maximum negative value at this point and does not reach 0 until the 90° point on the axis. At this point, however, curve 1 already has reached its maximum positive value and therefore leads curve 2 by 90°. It does not matter where this phase difference is measured, whether at the respective starting points of 1 and 2, at their respective positive maximum points, or at any other corresponding points. In B, two sine waves are 180° or one-half cycle out of phase. Curve 1 rises in the positive direction from the 0° starting point, whereas curve 2 rises in

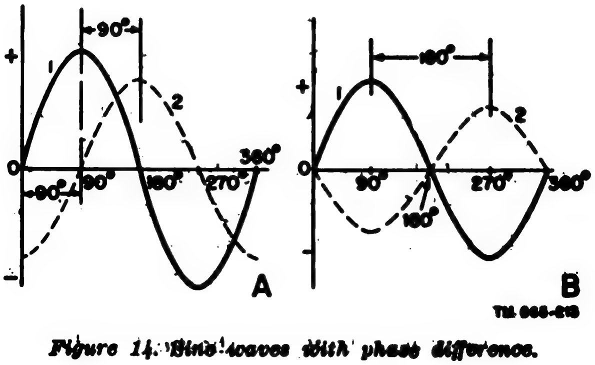


Figure 14. Sine waves with phase difference.

the negative direction from the same starting point. If the phase difference is measured between the positive maxima, it is seen to be 270° minus 90°, or 180°. It does not matter which of the two waves is considered as leading or lagging. Curve 2 is always positive and 1 is negative, and vice versa.

18. Vectors and Their Use

a. A vector is a segment (part) of a straight line that is pointed in a specific direction, and is used to represent the magnitude and direction of a given quantity. Magnitude is denoted by the length of the line segment, and direction is indicated by the orientation of the segment with respect to a base or reference line and by an arrow at the end of the line. For instance, if a selected location on a map lies 3 miles north of a certain position, this can be represented by a vector, say 3 inches long, which starts from the position and points north toward the selected location. A vector may represent *any* quantity which has *both* magnitude and a specific direction. If either the magnitude or the direction of the quantity (or both) varies with time, vectors can be drawn for each desired particular instant of time. Consequently, the vector represents the quantity only at these fixed instants.

b. A vector is not necessarily stationary. For instance, a point or an object rotating in a circle, such as a stone at the end of a cord, can be represented by a *rotating vector*, which continually indicates the distance and direction to the stone from the center of the circle. The rotating radius of figure 13, which illustrated the relation between a sine wave and a circle, is another example of a rotating vector.

c. Two or more vectors can be added or combined to find their *resultant*, which is also a vector. As an example, assume that a man is rowing a boat downstream at a speed of 4 mph (miles per hour) and in a direction parallel to the river banks (A of fig. 15). At the same time, assume that a cross wind is pushing the boat horizontally across the river toward the opposite bank at a speed of 3 mph. To find the resultant of these two motions, lay off to scale the velocity of the row boat in the absence of the cross wind as vector *OY*, in B. Then lay off vector *OX* at right angles to *OY*, representing the velocity of the boat under the influence of the cross wind alone. The two vectors are added by completing parallelogram *OYZX* and drawing in diagonal *OZ*. This diagonal represents the resultant or *vector sum* of both vectors. If the resultant is measured on the same scale as the two component vectors, it will be found to correspond to a velocity of 5 mph, and it forms an angle of 53.2° with the horizontal vector, *OX*. The process just described can be applied to more than two vectors by combining first two vectors by the parallelogram method and then combining the resultant vector with a third vector, and so on.

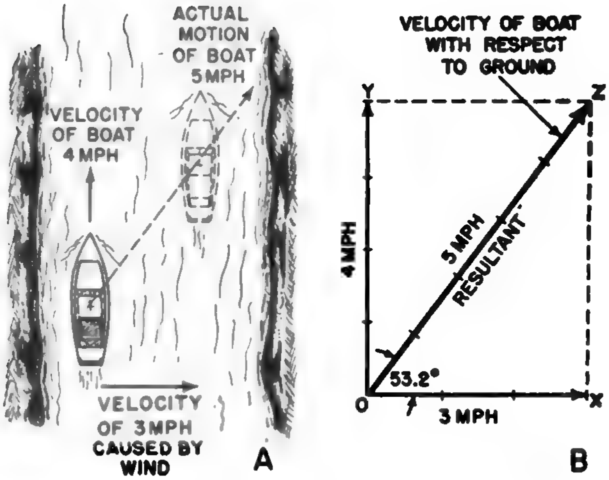


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Figure 15. Vector addition.

d. Two vectors may be subtracted from each other, by reversing the direction of the vector to be subtracted and then adding this reversed vector to the first. For example, if in A of figure 16, vector *OA* is to be subtracted from vector *OB*, then *OA* is simply reversed and $-OA$ is added to *OB* by the parallelogram method. The resultant vector, *OC*, represents the *vector difference OB* minus *OA*. If, on the other hand, in B, vector *OB* is to be subtracted from vector *OA*, then *OB* is reversed and $-OB$ is added to *OB*, resulting in *OC'*. The resultant vector, *OC'*, represents the vector difference *OA* minus *OB*. If more than two

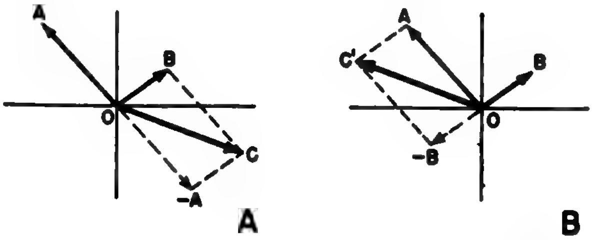

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Figure 16. Vector subtraction.

vectors are to be subtracted from each other, this can be done step by step by taking the vector difference of two vectors at a time.

19. Inductance

a. Self-Inductance.

(1) Inductance is that property of a circuit which accounts for the production of an induced voltage by a changing current. A voltage is induced in a conductor whenever magnetic flux lines cut across it. When a magnetic field is established around a coil of wire by connecting it to a d-c voltage source, the flux lines cut across adjacent wire turns and, consequently, induce a voltage in the coil. This induced voltage is always of such a polarity as to oppose the change of the current which produces it (caused by the applied voltage). Because the total induced voltage in the coil always *opposes any change* in the current, it is called a *cemf* (*counter* electromotive force). The greater the inductance in a circuit, the greater is the opposition to current changes—that is, the greater the counter electromotive force.

(2) If the coil is connected to an a-c voltage source, the magnetic field around the coil builds up in one direction, collapses to 0, builds up in the opposite direction, and collapses again, all in rapid sequence. This results in the continuous induction of counter electromotive forces which oppose the varying current flowing because of the applied voltage.

(3) The symbol for inductance is L and it is measured in *henrys*. If the current in a coil changes uniformly at the rate of 1 ampere per second and induces a voltage of 1 volt in the coil, its self-inductance is 1 henry. Smaller units, such as the mh (millihenry), representing one-thousandth of a henry, and the μh (microhenry), representing one-millionth of a henry, are frequently used. An assortment of air-core inductors is shown in figure 17.

b. Mutual Inductance. If an a-c voltage is applied to one coil, and its magnetic field lines link the turns of another nearby coil, an a-c voltage of the same frequency is induced in the second coil. The effect of magnetic flux linking two inductors is called *mutual inductance* (symbol M), and its magnitude is also measured in henrys. Again, the induced voltage is opposite in polarity to the inducing or exciting voltage. The amount of mutual inductance between two coils depends on their size and shape, their relative positions, and the magnetic permeability of the medium between them. Usually, not all of the magnetic field lines of one coil link the turns of a nearby coil. The extent to which two coils are coupled inductively is denoted by a coefficient of coupling which is unity for complete flux linkage.

c. Inductors in Series. If the spacing between coils is sufficiently great to make the effects of mutual inductance negligible, the total inductance of a number of inductors in series is

$$L=L1+L2+L3+L4+\ \ldots\ L_n$$

However, if two series-connected coils are spaced close together so that their magnetic field lines interlink, their total inductance is

$$L=L1+L2\pm 2M$$

where M represents the mutual inductance between the coils. The plus sign in the expression above is used if the coils are arranged in series-aiding—that is, in such a manner that the magnetic fields assist each other. The minus sign is used if the coils are connected in *series-opposing*—that is, so that the magnetic fields oppose each other.

d. Inductors in Parallel. If the coils are spaced sufficiently far apart that the mutual inductance between them can be neglected, the total inductance of a number of inductors arranged in parallel is

$$L=\frac{1}{1/L1+1/L2+1/L3+1/L4-\ \ldots\ 1/L_n}$$

For two inductors in parallel, which are not coupled together, the total inductance is

$$L=\frac{L1\times L2}{L1+L2}$$

It can be seen that the rules for combining inductors in parallel or series are the same as those for resistors.

e. Inductive Reactance and Phase Relations.

(1) It has been shown that in an a-c circuit the changing flux around an inductor induces a counter electromotive force in the coil which opposes the a-c current flow.

Figure 17. Assortment of air-core inductors.

This opposition is called *inductive reactance* and is designated by X_L. The magnitude of the cemf is directionly proportional to the *rate of change* of the current through the coil. The phase relations between current and voltage in a pure inductance are shown in figure 18.

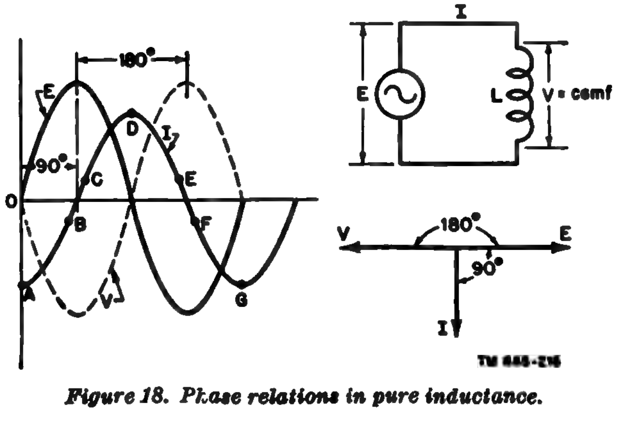

Figure 18. Phase relations in pure inductance.

At the instant of time chosen, the applied voltage, *E*, just begins its positive half-cycle. At that instant the cemf, *V*, just begins its negative half-cycle and is 180° out of phase with and equal to *E*. The current lags applied voltage, *E*, by 90° When the rate of change of current is instantaneously zero, the induced voltage, *V*, at this point is also 0. In the regions between *B* and *C*, and between *E* and *F*, where the current passes through 0, the slope is steepest. The rate of change of the current is maximum and hence the induced voltage, *V*, reaches a maximum in these regions. This implies a 90° phase difference. In the vectorial diagram, *E*, has arbitrarily been drawn horizontally and to the right. The cemf, *V*, is then equal and opposite, as indicated. Current *I* lags 90° behind *E*, as shown.

Its magnitude depends on the inductive reactance, X_L.

(2) A pure inductance is unattainable in practice, since any coil which is wound with wire has some resistance. This resistance can be considered as separate and in series with the inductance (A of fig. 19). If an alternating current flows through the coil, a voltage drop occurs across both the resistance and the inductance. The voltage across the coil, E_L, leads the current by 90°, and the voltage drop across the resistance, E_R, is in phase with the current. However, the vector sum of E_L and E_R at every instant must be equal to the applied voltage, E, as shown in C. The actual waveforms of E, E_L, E_R, and I are shown in B.

(3) The rate of change of an alternating current is directly proportional to its frequency, since more cycles must be completed in a given time as the frequency increases. Hence, the cemf in an inductor also is proportional to the supply frequency, and, further, to the inductance, as previously stated. The inductive reactance, X_L, which is a measure of this cemf, therefore is proportional to both the frequency and the inductance. The formula for inductive reactance is

$$X_L = 2\pi f L$$

where X_L is the inductive reactance in ohms, f is the frequency in cycles per second, and L is the inductance in henrys. *Example:* The inductive reactance of a

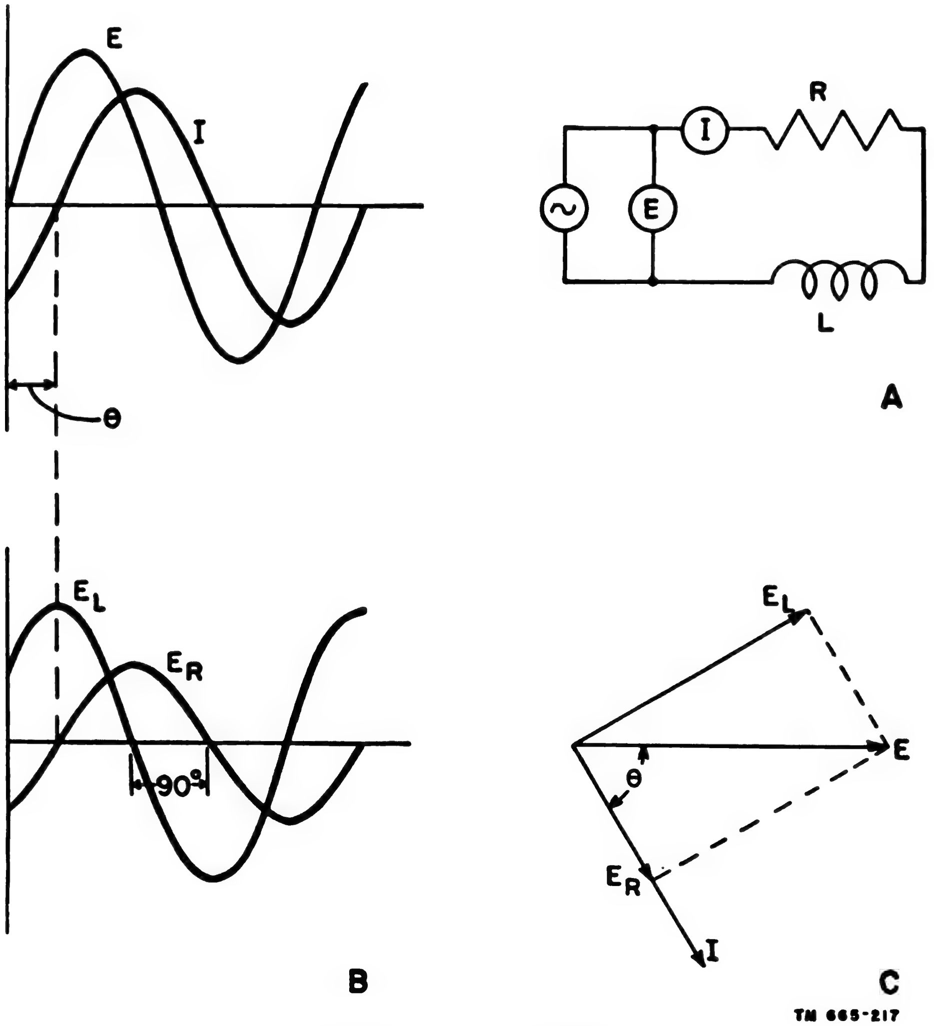

Figure 19. Phase relations in resistive inductor.

coil having an inductance of 8 henrys at a frequency of 120 cps is

$$X_L = 6.28 \times 120 \times 8 = 6{,}029 \text{ ohms.}$$

f. Transformers.

(1) Two coils coupled by mutual inductance constitute a transformer. The magnetic field may link the coils either through an iron core or an air core, the latter usually being used at radio frequencies. The coil connected to the a-c voltage supply is called the *primary* winding. The other coil, which ordinarily is connected to a load, is called the *secondary* winding. A transformer is useful for transferring electrical energy from one circuit to another without direct connection, and for stepping up or stepping down voltage or current levels. In a transformer having a closed iron core, practically all of the magnetic flux lines produced by the primary winding link every turn of the secondary winding. Such a transformer is almost perfect, since it has practically no leakage flux. For a given magnetic field, the voltage induced in the primary coil is proportional to the number of turns in its winding, and since the secondary coil of a perfect transformer is in the same field, the voltage induced in the secondary is proportional to the number of secondary turns. Hence, for a perfect iron-core transformer, the ratio of primary to secondary voltage is equal to the ratio of the number of turns in the two windings. Stated conveniently in mathematical form

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

where E_p and E_s are the primary and secondary voltages, respectively, and N_p and N_s are the number of turns in the primary and secondary windings. This formula does not apply to air-core transformers where considerable flux leakage exists. Some typical air-core power transformers are shown in figure 20.

Example: An iron-core transformer has a primary winding of 500 turns, a secondary winding of 3,500 turns, and 115 volts is applied to the primary. What is the voltage across the secondary?

$$E_s = \frac{N_s}{N_p} \times E_p = \frac{3{,}500}{500} \times 115 = 7 \times 115 = 805 \text{ volts}$$

(2) If the magnetic fields in the primary and secondary of an iron-core transformer are equal, their respective magnetizing forces must be equal. The magnetizing force of a coil is expressed as the product of the number of turns times the current flowing in the coil (called *ampere turns*). Consequently, the primary current multiplied by the primary turns must equal the secondary current multiplied by the secondary turns. This may be written

$$N_p \times I_p = N_s \times I_s, \text{ or } \frac{I_s}{I_p} = \frac{N_p}{N_s}$$

Comparing this expression with the previous expression, it is apparent that the current is stepped down when the voltage is stepped up, and vice versa.

20. Capacitance

a. General. Two or more conductors separated from each other by an insulating medium (called a *dielectric*) form a capacitor. The simple capacitor shown in figure 21 consists of two closely spaced parallel metal plates. Normally, with the switch open, the two plates are electrically neutral; that is, the number of positive and negative charges on each plate are equal, and there is no net electric charge. The capacitor can be charged by closing switch *S* to connect it to the terminals of a battery. At the instant the switch is closed, the positive terminal of the battery attracts electrons from the plate connected to it, and the same number of electrons are repelled from the negative battery terminal into the plate connected to it. Electrons continue to be removed from one plate (mark + in fig. 21) and flow, via the battery, into the other plate (marked −), until a state of equilibrium is reached in which the potential difference between the plates equals the voltage of the battery. The electron flow (current) is practically instantaneous, and it stops as soon as the capacitor is charged to the same voltage as that of the battery. If the switch is now opened, the positive plate of the capacitor is left with a deficiency of electrons and the negative plate with an excess of electrons. In other words, the plates remain

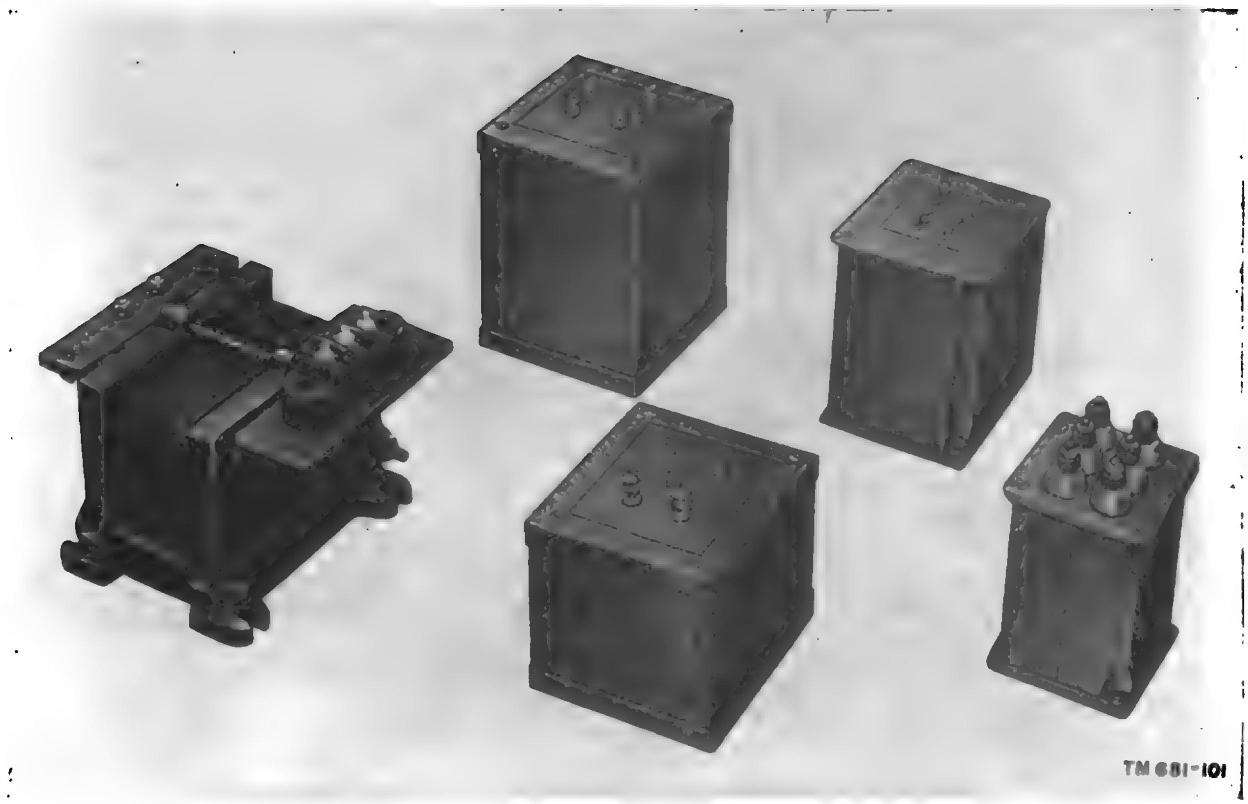

Figure 20. Power transformers.

charged although they are no longer connected to the battery.

b. Electric Field. A capacitor has the ability to store electrical energy. This energy can be considered to be stored in the form of an *electric field* which exists between the two plates because of their difference of potential. Just as in the case of a magnetic field, the electric field is represented by imaginary lines of force whose density indicates the strength of the field. These lines of force show the paths along which a free electron would move if inserted between the two plates. The lines of force are directed toward the positively charged plate, since an electron would move toward it if inserted in the electric field. The field collapses almost instantaneously if the capacitor is discharged by short-circuiting the two plates by a conductor.

Figure 21. Simple capacitor.

c. Capacitance Definition. If the capacitor in figure 21 is connected to a battery with a higher voltage, it acquires a greater charge until its plates attain a potential difference equal to the higher battery voltage. In other words, the higher the applied voltage, the greater is the voltage between the plates and the greater is the charge on the capacitor. However, the ratio of the charge, Q, on the plates to the potential difference, E, between them always remains the same for any particular capacitor, and this is called the *capacitance*, C. In equation form capacitance

$$C=\frac{Q}{E}$$

If a potential difference of 1 volt charges a capacitor with 1 coulomb of electricity, its capacitance is 1 *farad* (the unit of capacitance). This is a tremendously large unit. Practical values of capacitance used in electronics are the μf (microfarad), which is one-millionth of a farad,

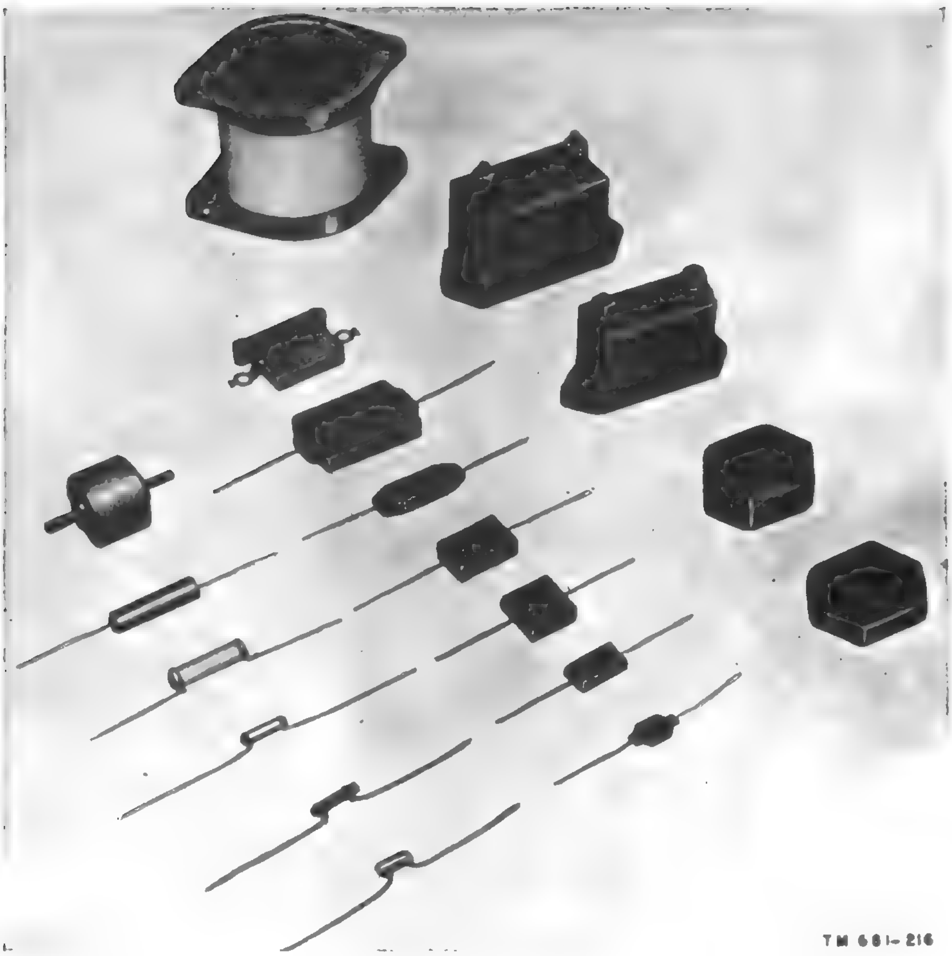

Figure 22. Typical mica and ceramic capacitors.

and the μμf (micromicrofarad), which is one-millionth of a microfarad. The capacitance of a capacitor increases with the size and number of plates used and decreases as the distance between the plates is increased. Capacitance also depends on the type of dielectric material used between the plates. Figure 22 shows some typical mica and ceramic capacitors.

d. Capacitors in Series. The total capacitance of capacitors in series is calculated in the same way as resistors in parallel. If all of the capacitors are the same, the value of one of the capacitors is divided by the number used. For two unequal capacitors in series, the total capacitance is

$$C=\frac{C_1\times C_2}{C_1+C_2}$$

For more than two capacitors in series, the total capacitance is

$$C=\frac{1}{1/C_1+1/C_2+1/C_3+1/C_4+\ \dots\ 1/C_n}$$

e. Capacitors in Parallel. Capacitors in parallel are treated in the same way as resistances in series. The total capacitance is found by adding the values of all individual capacitors, or

$$C=C_1+C_2+C_3+C_4+\ \dots\ C_n$$

f. Phase Relations and Capacitive Reactance.

(1) A capacitor that is connected to an a-c voltage source becomes charged alternately in opposite directions, and electrons surge to and fro in the connecting wires. The electrons cannot actually flow through the dielectric medium between the plates. However, since an alternating current flows back and forth in the connecting wires at the supply frequency, it is referred to loosely as flowing *through* the capacitor. When the voltage first is applied to the uncharged capacitor, the capacitor draws a large charging current.

As soon as the charge on the capacitor reaches the applied voltage, the current drops to 0 (fig. 23), since the capacitor cannot be charged to a voltage higher than that applied. In other words, the current is greatest at the beginning of the voltage cycle and becomes 0 at the maximum value of the voltage. When the applied voltage starts to decrease from its maximum value, the capacitor begins to discharge. The current flows in the opposite direction. Consequently, the current through the capacitor leads the voltage across it by 90°.

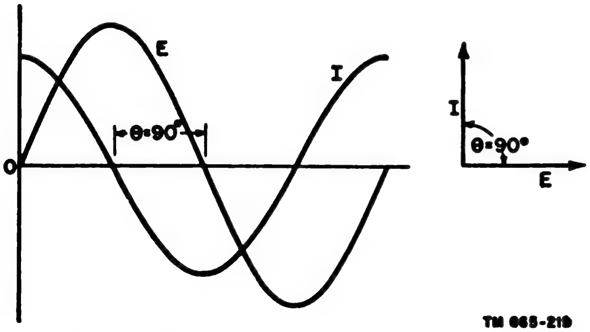

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Figure 23. Phase relations in capacitor.

(2) A capacitor offers a certain opposition to the flow of alternating current, which is called *capacitive reactance.* The symbol for capacitive reactance is X_C and it is measured in ohms. The greater the capacitance, the greater is the charge for a given voltage and hence the greater the charging current. As a result, the opposition to the current is smaller. Therefore, the capacitive reactance (the opposition to current flow) and the capacitance are *inversely* related. Also, the higher the frequency, the more rapid is the transfer of charge in and out of the capacitor. As a result, at higher frequencies, there is a larger current or a smaller opposition to current flow. This is described by saying that the capacitive reactance is inversely proportional to the frequency. Combining these two observations in mathematical form and inserting the factor 2π, the capacitive reactance in ohms is

$$X_C=\frac{1}{2\pi f C}$$

where f is in cycles per second and C is in farads. If C is given in microfarads, and f in megacycles, the reactance, X_C, also will be in ohms.

Example: The capacitive reactance of a .002-μf capacitor at a frequency of 2.5 megacycles is

$$X_c=\frac{1}{6.28\times 2.5\times 106\times .002\times 106}=31.8 \text{ ohms}$$

21. Alternating-Current Circuits

a. Impedance.

(1) It has been shown that the voltage across a pure inductance leads the current by 90° and that the voltage across a pure capacitance lags the current by 90°. For this reason, the inductive reactance in a circuit containing both inductance and capacitance is considered positive and the capacitance reactance is considered negative to show that their effects are 180° out of phase with each other. The net reactance, X, in such a circuit is found by subtracting one reactance from the other. If X_L is larger than X_C, the net reactance is inductive (positive), and if X_C is larger than X_L, the net reactance is capacitive (negative).

(2) The total opposition to the flow of alternating current is termed *impedance*, and it is designated by the symbol Z. Impedance includes the opposition to current flow caused by both resistance and reactance, and it is measured in the same unit, the ohm. Resistance and reactance cannot be simply added together to give impedance, because there is a phase angle of 90° between them, and they are fundamentally of different nature. Only the resistance absorbs electric energy and usually converts it to heat, whereas reactance stores electric energy temporarily in the form of a magnetic or an electric field. The impedance can be represented by the hypotenuse of a right triangle, the shorter sides of which are made up by the resistance and the net reactance. Such an *impedance triangle*, with the resistance laid off along the horizontal side and the reactance along the vertical

side, is shown in figure 24. The impedance of an a-c circuit, therefore, equals the square root of the sum of the squares of the resistance and the net reactance. The formula for the impedance of an a-c circuit is

$$Z=\sqrt{R^2+X^2}=\sqrt{R^2+(X_L-X_C)^2}$$

If either the inductive or the capacitive reactance is absent, X_L or X_C drops out of the preceding equation. The tangent of the included angle, θ, in a right triangle is the ratio of the opposite side to the adjacent side. Hence, the tangent of this angle which represents the phase angle is the ratio of the net reactance to the resistance,

$$\tan \theta=\frac{X}{R}$$

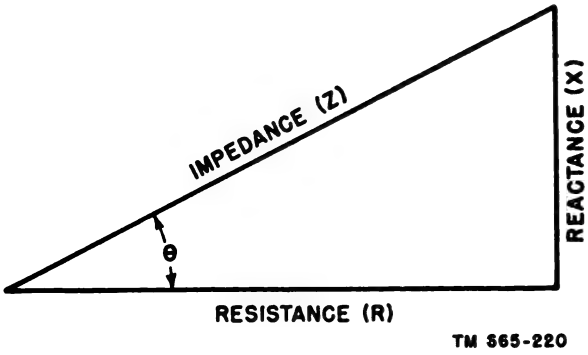

Figure 24. Impedance triangle.

(3) Ohm's law can be applied to a-c circuits by substituting impedance, Z, for resistance, R. Therefore

$$I=\frac{E}{Z}=\frac{E}{\sqrt{R^2+(X_L-X_C)^2}}$$

$$E=I\times Z=I\times\sqrt{R^2+(X_L-X_C)^2}$$

and $Z=E/I$.

b. A-C Voltage Dividers. A-c voltage dividers may take a great variety of forms, since any combination of resistors, capacitors, and inductors can be used to divide the applied voltage in a certain proportion. A few simple types are shown in figure 25. A, B, and C show circuits which use circuit constants of the same kind within each divider, and therefore the output voltage, E, is in phase with the input voltage, V. Here a voltage reduction alone is accomplished. Many times, however, it is desired to shift the phase of the output voltage with respect to that of the input voltage, as well as to reduce its magnitude. This can be done by using combinations of different circuit constants, as shown in D, E, and F. An expression is given in each case for the output voltage, E, in terms of the input voltage, V, and the constants. In general, the ratio of the output to the input voltage equals the ratio of the output impedance, across which the output voltage appears, to the total impedance of the voltage divider. However, this is correct only if the load across the output terminals draws a negligible current.

c. Resonant Circuit.

(1) It has been shown that the inductive reactance increases with frequency, whereas

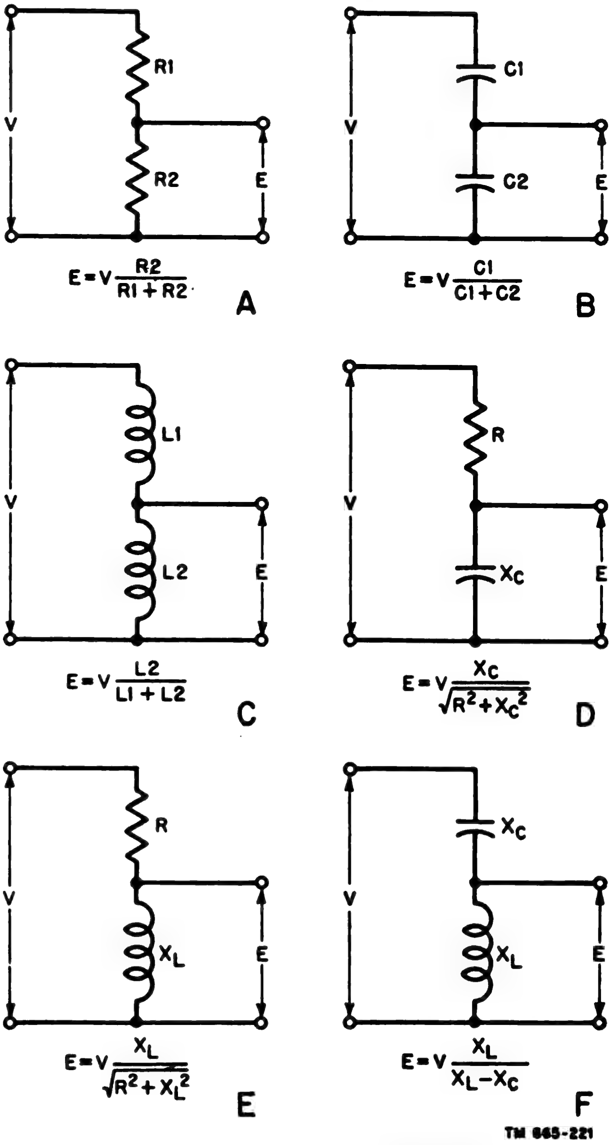

Figure 25. A-c voltage dividers.

the capacitive reactance decreases with frequency. At some frequency, then, they are equal, the net reactance being equal to 0. The frequency at which this occurs is known as the *resonant* frequency, and an R-L-C circuit at this frequency is said to be in tune or in resonance. Reasonant circuits are useful because of their ability to select or reject certain frequencies. At resonance, $X_L = X_C$, or

$$2\pi fL = \frac{1}{2\pi fC}$$

Solving for the resonant frequency,

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where f is in cycles per second, L is in henrys, and C is in farads. This formula is true when R is negligible.

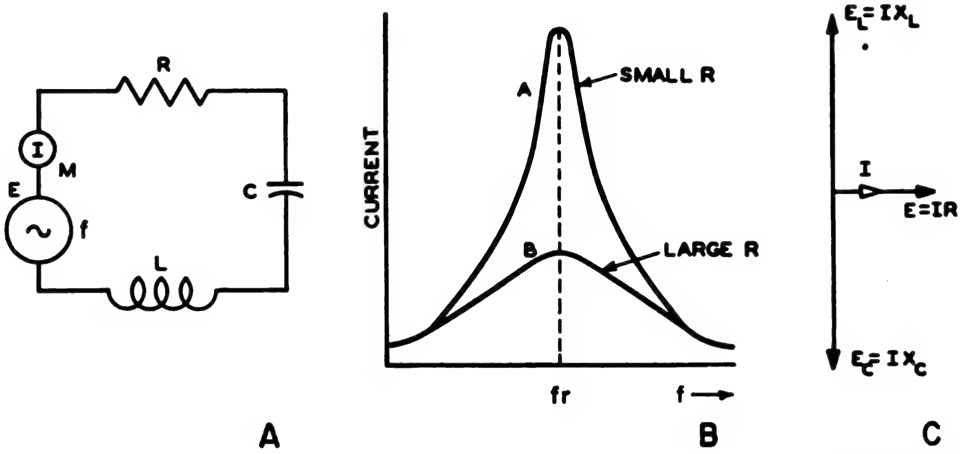

Figure 26. Series resonance.

(2) A *series-resonant* circuit (A of fig. 26) consists of a combination of resistance, inductance, and capacitance and a source of voltage (applied voltage) connected in series. At resonance, the inductive and capacitive reactances are equal and opposite to each other, and hence the current in the circuit is limited only by the resistance. The line current for a series-resonant circuit is, therefore,

$$I = \frac{E}{R}$$

where E is the applied voltage and R is the total resistance of the circuit. If the total resistance of the circuit is small, as in C, the line current can be very large, and as a result the voltage drops across the inductor and the capacitor may be many times the applied voltage. At frequencies below resonance, the capacitive reactance predominates, and the circuit acts like a capacitor in series with a resistance. At frequencies above resonance, the inductive reactance predominates, and the circuit behaves like an inductance in series with a resistance. If a graph of line current against frequency is plotted, as in B, the resultant curve is a *resonance curve.* With a small circuit resistance the current rises sharply near the resonant frequency, whereas with a large circuit resistance the curve is relatively broad and flat, as shown in the figure. The circuit represented by curve A is said to be much more *selective* than that represented by curve B, since such a circuit would be better able to discriminate against frequencies on either side of resonance. This is an important characteristic of tuned circuits.

(3) The sharpness of the resonance curve is determined by a quality factor called Q. It is defined as the ratio of the reactance of either the coil or the capacitor at the resonant frequency to the total resistance of the circuit, or

$$Q = \frac{X_L}{R} = \frac{2\pi fL}{R}, \text{ or } Q = \frac{X_C}{R} = \frac{1}{2\pi fCR}$$

Since nearly all of the resistance in the circuit is associated with the coil, the first expression is more frequently used, and is more significant. Q is also a measure of the ratio of the reactive power stored in the circuit to the actual power dissipated in the resistance. The higher the Q, the greater the amount of energy stored in the circuit compared with the energy lost in the resistance during each cycle, and, consequently, the greater the efficiency of the tuned circuit.

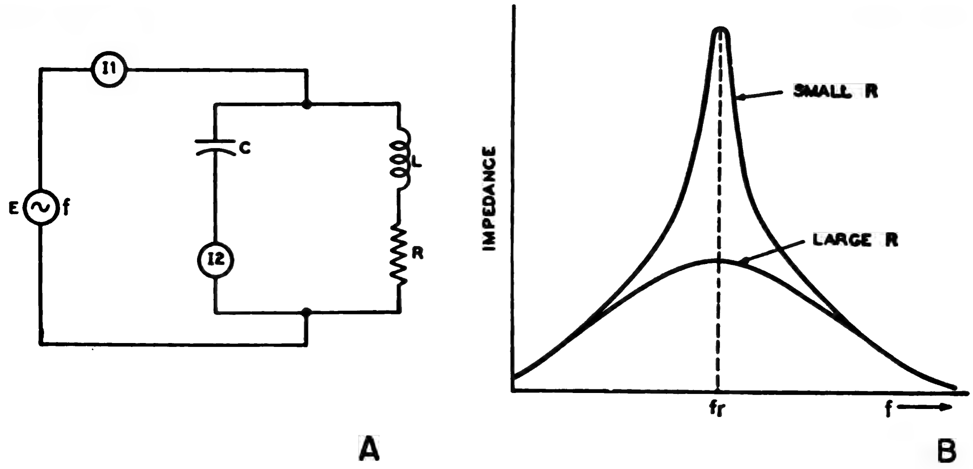

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Figure 27. Parallel resonance.

(4) A *parallel-resonant* circuit consists of two branches in parallel with a source of voltage (applied voltage) one branch containing inductance, and the other containing capacitance (A of fig. 27). The resistance shown in the illustration represents that contained in the coil and the associated conductors plus any added resistors. Since the capacitive reactance equals the inductive reactance at resonance, the currents through the two branches are about equal in amplitude, but opposite in phase in respect to the line. Therefore, they cancel each other in the external line circuit, and only the current resulting from the loss caused by the resistance flows in the line. Although the line current, $I1$, is very small, the current circulating in the two branches, $I2$, can be very large with a high-Q circuit. This circulating current, $I2$, is approximately equal to Q times $I1$, where $I1$ is the line current. The line current is a *minimum* at resonance and it increases above and below resonance. Therefore, the impedance presented by the parallel branches is correspondingly large at resonance. Depending on the circuit resistance, it approaches its maximum value at resonance more or less sharply, as shown by the impedance curves in *B*. The impedance is purely resistive and its value is

$$Z=\frac{X_L X_C}{R}=\frac{L}{CR}$$

The impedance of a parallel-resonant circuit can be expressed also in terms of Q and the reactance of either coil or capacitor, as

$$Z=QX_C \text{ or } Z=QX_L=2\pi fLQ$$

The line current at resonance is then simply

$$I_1=\frac{E}{Z}=\frac{E}{QX}$$

where X is the reactance of either coil or capacitor. As a consequence of these relations, the higher the Q of a parallel-resonant circuit, the greater the resonant impedance and the circulating current, and the smaller the line current. Because of its ability to act like a storage tank for electric energy, a parallel-resonant circuit is known also as a *tank circuit*, and fulfills an important function in radio transmitters and receivers.

d. Filter.

(1) *General.* A filter is a circuit consisting of a number of impedances grouped together in such a way as to have a definite frequency characteristic. Filters are designed to transmit (permit passage) freely over a certain range of frequencies and to transmit poorly over another range of frequencies. The range over which transmission occurs freely is called the *pass band*, and the range over which poor transmission occurs is called the *attenuation band.* The frequency at which attenuation starts to increase rapidly is known as th *cut-off frequency.* Basic configurations into which filter elements can be assembled are the *L*- or *half-section*, consisting of one series and one parallel (shunt) arm; the *full T-section*, consisting of two series arms and one shunt arm (resembling the letter T); and the full *π-section*, consisting of one series arm and two shunt arms (resembling the Greek letter π). Several sections of the same configuration can be joined to improve the attenuation or transmission characteristic. When filters are inserted in a circuit, they usually are terminated by resistances of the same value at both the input and the output end. The value of the terminating resistance usually is determined by the circuit with which the filter is used. The desired cut-off frequencies are predetermined also. Knowledge of the values of capacitors and inductors to give the desired frequency characteristic (fig. 28) is necessary when designing a filter.

(2) *Low-pass filters.* Low-pass filters transmit freely frequencies below the cut-off frequency, f_c, and transmit poorly frequencies above that value. To understand the action, consider the T-section filter in figure 28. At high frequencies the inductive reactance of the two coils in series is large, and hence they offer large opposition to the flow of current toward the output termination (load). Also, any high-frequency current that does get through the first coil passes through the capacitor, whose reactance to high frequencies is low, and does not reach the output. For low-frequency currents, however, the inductive reactance is small and the capacitive reactance is large. Accordingly, these currents readily pass through both coils to the load. This is shown graphically by the transmission characteristic curve. The required values of inductance and capacitance, in terms of the cut-off frequency, f_c, and the termination resistance, R, are shown in the figure. Full values of L and C are used for the half-section; for the T- and the π-sections these values are halved, as shown.

(3) *High-pass filters.* High-pass filters transmit freely frequencies above the cut-off frequency, f_c, and transmit poorly frequencies below that value. Their action in the case of a T-section high-pass filter, for example, is as follows (fig. 28): At low frequencies the capacitive reactance is large, so that the two capacitors in series offer large opposition to the flow of current. Any low-frequency current from the input that does get through the first capacitor passes through the coil, whose reactance at low frequencies is small; therefore, it does not reach the output. For high-frequency currents, the capacitive reactance is small and the inductive reactance is large. Consequently, these currents pass readily through both capacitors to the output end, and very little current is diverted through the coil.

(4) *Band-pass filters.* Band-pass filters transmit freely in a range of frequencies, limited by two cut-off frequencies, $f1$ and $f2$, and transmit poorly on each side of that range, below $f1$ and above $f2$ (fig. 28). They can be considered as made up of a low-pass filter and a high-pass filter, whose regions of free transmission overlap.

(5) *Band-rejection filters.* Band-rejection filters transmit poorly in a range of frequencies, limited by two cut-off frequencies, $f1$ and $f2$, and transmit freely on both sides of that range (fig. 28). A low-pass filter and a high-pass filter in parallel act as a band-rejection filter, provided their regions of poor transmission overlap.

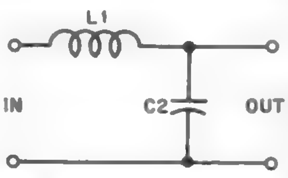
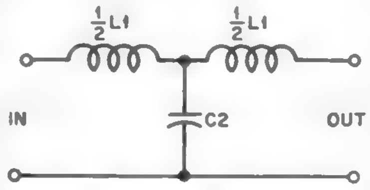
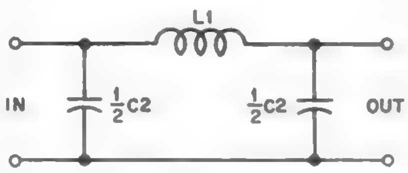
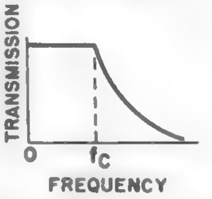
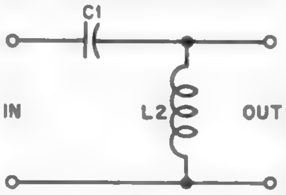
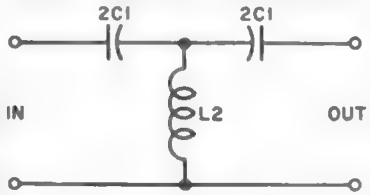
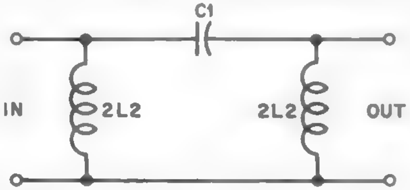
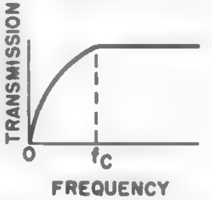
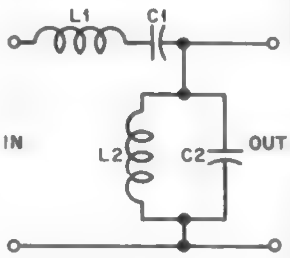
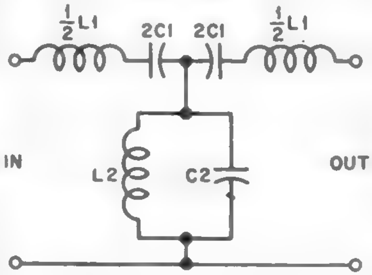
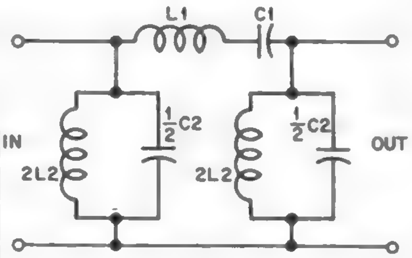
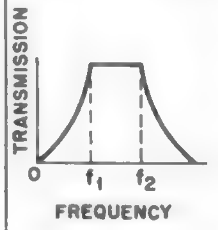
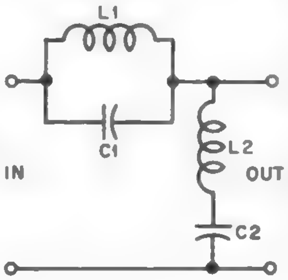
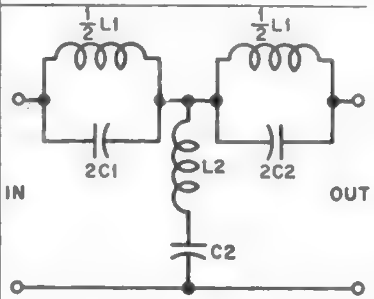
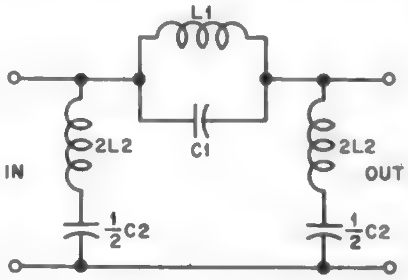
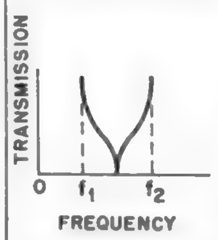
TYPE	HALF-SECTION	T-SECTION	π-SECTION	CIRCUIT PARAMETERS (f_C IS CUT-OFF FREQUENCY. R IS TERMINATING RESISTANCES)	TRANSMISSION CHARACTERISTIC
LOW-PASS				$L1=\frac{R}{\pi f_C}$ $C2=\frac{1}{\pi f_C R}$	
HIGH-PASS				$C1=\frac{1}{4\pi f_C R}$ $L2=\frac{R}{4\pi f_C}$	
BAND-PASS				$L1=\frac{R}{\pi(f_2-f_1)}$ $L2=\frac{(f_2-f_1)R}{4\pi f_2 f_1}$ $C1=\frac{f_2-f_1}{4\pi f_2 f_1 R}$ $C2=\frac{1}{\pi(f_2-f_1)R}$	
BAND-REJECTION				$L1=\frac{(f_2-f_1)R}{\pi f_1 f_2}$ $L2=\frac{R}{4\pi(f_2-f_1)}$ $C1=\frac{1}{4\pi(f_2-f_1)R}$ $C2=\frac{f_2-f_1}{\pi f_1 f_2 R}$	

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Figure 28. Simple filter sections.

(6) *Wave traps.* A wave trap can be a simple parallel-resonant circuit, tuned to a frequency which is to be rejected. This is inserted in series with the circuit which normally transmits the frequency to be rejected. It has been shown previously that a circuit consisting of a coil and a capacitor in parallel has an extremely high impedance at its resonant frequency and permits very little line current to flow at this frequency. By providing a variable capacitor for tuning, it is possible to reject any particular frequency within a certain band. Wave traps frequently are inserted between the antenna and the antenna terminals of a receiver to eliminate specific interfering signals. Several wave traps can be connected in series to reject several different interfering frequencies.

e. Impedance Matching.

(1) Many devices require a specific value of load resistance or impedance for optimum operation. The resistance of the actual load may unavoidably differ widely from this optimum value. A transformer can be used to convert the actual value of load resistance to the desired magnitude. This is one method of *impedance matching.* Generally, maximum power is transferred to a load when the impedance of the load equals that of the source. To accomplish maximum power transfer is an important function of impedance matching.

(2) The relationships between primary and secondary voltages and currents in an iron-core transformer have been given. With these relationships, it is possible to solve for the ratio of the impedance of the primary winding, Z_p, to the impedance of the secondary winding, Z_s, by substituting $Z_s=E_s/I_s$, and $Z_p=E_p/I_p$. It is then found that the ratio of the primary to secondary impedance is

$$\frac{Z_p}{Z_s}=\left(\frac{N_p}{N_s}\right)^2 \text{ or } \frac{N_p}{N_s}=\sqrt{\frac{Z_p}{Z_s}}$$

Therefore, in an iron-core transformer with almost perfect coupling, the impedance ratio is equal to the *square* of the turns ratio.

Example: An electron tube audio amplifier requires a load of 3,000 ohms for optimum performance and it is to be connected to a loudspeaker having an impedance of 6 ohms. The primary-to-secondary turns ratio required in the output transformer is then

$$\frac{N_p}{N_s}=\sqrt{\frac{Z_p}{Z_s}}=\sqrt{\frac{3{,}000}{6}}=\sqrt{\frac{500}{1}}=\frac{22.4}{1}$$

The primary winding, therefore, must have 22.4 times as many turns as the secondary winding.

(3) An iron-core transformer cannot be used at radio frequencies because of excessive losses in the core. In figure 29, A shows a circuit frequently used in radio transmitters for coupling a radio-frequency amplifier to a resistive load. Here the r-f energy from the tank circuit is coupled to the load by means of an air-core transformer, consisting of coils *L*1 and *L*2. In this circuit the impedances are matched by adjusting the mutual inductance be-

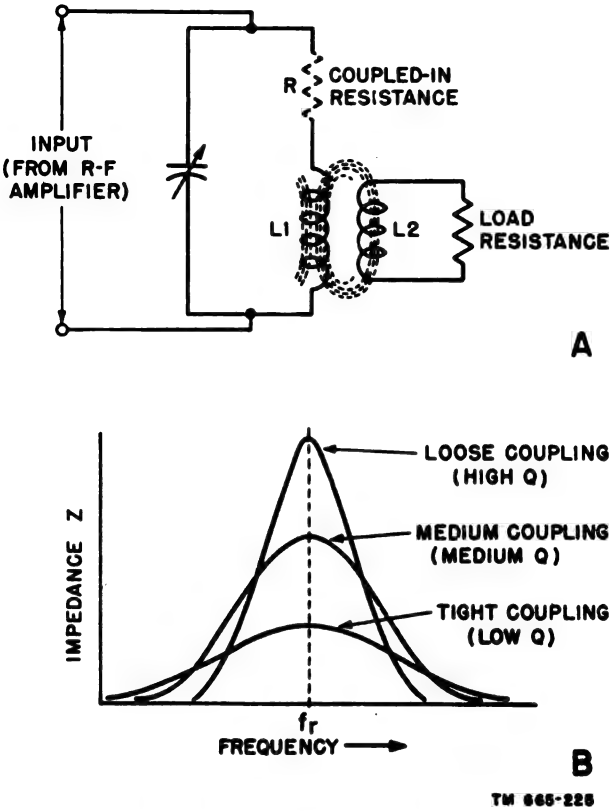


Figure 29. Effect of variable coupling in air-core transformer.

tween the coils. This can be done by changing the number of turns in the untuned coil or by varying the coupling between the coils.

(4) The load resistor to which the untuned coil, *L*2, is connected is coupled into the tuned tank circuit in proportion to the coupling between the coils. This affects coil *L*1 in exactly the same manner as though a resistor had been added in series with it. The resistance coupled into the tank circuit can be considered as being *reflected* from the load (secondary) circuit into the tank (primary) circuit. By increasing the effective series resistance of the tuned circuit, the coupled-in resistance lowers the *Q* of the latter and hence its selectivity. When the coupling between the coils is small, the circuit is said to be loosely coupled. In B of figure 29, the coupled-in resistance, *R*, is also small, circuit *Q* is high, and the resonance curve is sharp. When the coupling is increased somewhat, the circuit is said to have medium coupling. The coupled-in resistance is larger than before, circuit *Q* is lower, and the resonance curve is broader. When the coupling between the coils is very close, the circuit is said to have tight coupling. Then the resistance reflected into the tank circuit is large, circuit *Q* is low, and the resonance curve is very broad.

Section IV. ELECTRON TUBES

22. Diode

The simplest form of electron tube is the diode, consisting of two electrodes, a cathode, and a plate. The cathode may be directly heated or indirectly heated. An evacuated glass or metal envelope incloses the elements. Figure 30 shows some typical diodes.

a. Operation. When a positive potential is applied to the plate of the diode, electrons flow from the cathode to the plate, and return to the cathode through the external circuit. This flow of electrons is known as *plate current.* If a negative potential is applied to the plate, however, no plate current flows, because the emitted electrons are repelled from the negative plate. Therefore, electrons can flow from the cathode to the plate only when the plate is positive in respect to the cathode. Electrons cannot flow from the plate to the cathode.

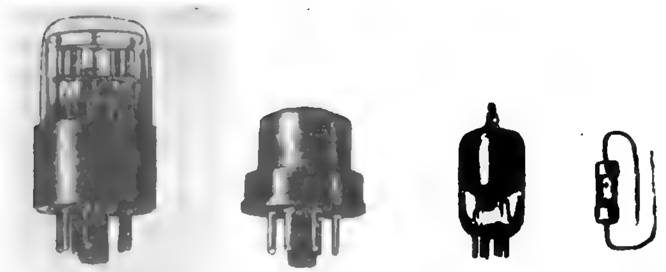
b. Space Charge. For a given cathode temperature, the maximum number of emitted electrons is fixed. However, not all of these emitted electrons reach the plate. Some electrons form a cloud in the space between cathode and plate and constitute a negative *space charge*, which tends to repel other electrons leaving the cathode surface. The higher the plate voltage, the higher is the plate current as the space charge effects are neutralized. If a sufficiently high plate voltage is applied, all the electrons emitted by the cathode, at a given temperature, are drawn to the plate. This represents a maximum plate current, called saturation current. Higher plate voltages do not produce a further increase in plate current. At high plate voltages, then, the plate current is practically independent of the plate voltage, but depends primarily on the cathode temperature. At low plate voltages, the plate current depends on the plate voltage, and is independent of the temperature of the cathode.

c. Use. If an a-c voltage is applied to the plate of a diode, plate current flows only during the positive half-cycles, when the plate is positive. Since current can flow in only one direction, it is said to be *rectified.* Diode rectifiers are used extensively in radio transmitters, receivers, and auxiliary equipment. The unidirectional characteristic of the diode is used also in detector circuits, which extract the original modulation from a modulated radio-frequency carrier wave. Diodes also are used in many wave-shaping and other special circuits.

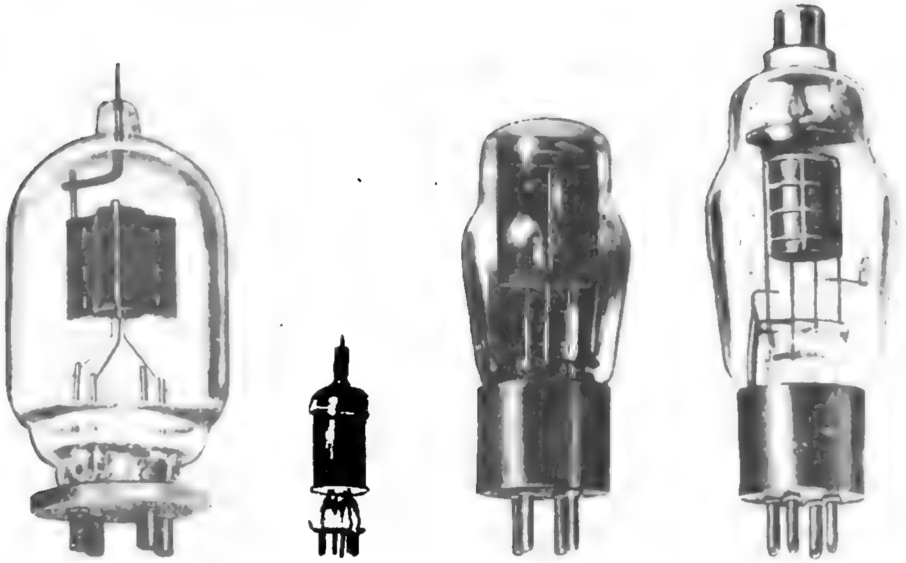
23. Triode

When a third electrode, called the control *grid*, is placed between cathode and plate, the arrangement constitutes a *triode.* The grid usually is a mesh or winding of fine wire around the cathode.

a. Operation. Because of its mesh construction, the grid does not impede passage of electrons from cathode to plate. The purpose of the grid is to control the flow of plate current. The number of electrons reaching the plate depends on both the plate and the grid potential. In an amplifier, the grid voltage normally is at a negative value. If the plate voltage is positive, and the grid voltage is made more and more negative, progressively more electrons are repelled by the grid and fewer are attracted to the plate. As a result, the plate current decreases. At a certain negative grid voltage, known as the *cut-off bias*, all electrons are forced back to the cathode, and hence the plate current is zero. If the grid voltage is made less and less negative (more positive), progressively more electrons get through the grid and are attracted to the plate. Therefore, the plate current increases. If an a-c signal voltage is applied to the grid, the plate current varies in accordance with the signal. A relatively small voltage change on the grid can cause a large change in plate current.



SIGNAL DIODES



POWER DIODES

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Figure 30. Typical diodes.

b. Amplification. The plate current in a triode is affected to a much greater degree by a change in the grid voltage than by a change in the plate voltage. A slight change in grid voltage has the same effect on the plate current as a greater change in the plate voltage. This permits the triode to be used as an amplifier because grid voltage variations are amplified in the plate circuit.

(1) *Voltage amplification.* When a resistance or an impedance load is inserted in the plate circuit, the voltage drop across the load depends on the plate current. The plate current, in turn, is controlled by the grid voltage for a fixed plate voltage. Because of the amplifying action of the tube, a small change in grid voltage produces a large change in the voltage across the load. By making the load resistance large, a large voltage drop is

produced across it, resulting in high voltage amplification. The plate current, however, is small, and so is the output power.

(2) *Power amplification.* In the output stages of receivers and transmitters, relatively large amounts of power are required. Triode tubes designed for this application sacrifice high voltage amplification to produce large amounts of power output. Power amplifier tubes have a moderate amplification factor and a low internal plate resistance. They are, therefore, capable of providing large plate currents at high plate voltages, a requirement for high power output. Except for inherent design differences, the principles of power amplification are the same as those for voltage amplification.

(3) *Load considerations.* It has been pointed out that the amplification of a voltage amplifier increases with the value of the load resistance. If the plate load resistor is made too large, however, the voltage drop across it reduces excessively the plate voltage applied to the tube. As a result, the voltage output of the tube is reduced. Commonly used values of load resistance for voltage amplifiers are from 10 to 50 times the internal plate resistance of the tube. For a resistance-coupled amplifier, the grid-input resistance of the following stage is effectively in parallel with the plate-load resistance. Its value must, therefore, also be high to prevent too much shunting of the load resistor. For a power amplifier, on the other hand, the load must be matched to the plate resistance of the tube, and is, therefore, of a fairly low value. It has been pointed out that maximum power transfer occurs in a circuit if the load resistance equals the internal resistance (plate resistance) of the source. However, excessive distortion may result under this condition. For this reason the load resistance usually is made from two to three times the plate resistance of the tube. This is a good compromise between distortion and power output considerations.

(4) *Classes of amplifiers.*

(*a*) *Class A.* A class A amplifier is operated so that plate current flows at all times, and hence the waveshape of the output voltage is essentially the same as that of the signal voltage applied to the grid. A class A amplifier is biased so that the grid is always negative.

(*b*) *Class AB.* A class AB amplifier is operated so that plate current flows for appreciably more than one-half but less than the entire cycle. The grid is biased so that it is driven to cut-off during part of the negative half-cycle of the grid input signal. Consequently, some distortion is present in the output waveshape. Push-pull design is used in class AB operation.

(*c*) *Class B.* A class B amplifier is operated so that the grid bias is approximately equal to the cut-off value and therefore the plate current is zero in the absence of an exciting grid voltage. When an a-c grid voltage is applied, plate current flows for approximately one-half of each cycle, and considerable distortion of the output waveshape takes place. Push-pull design also is used in class B operation.

(*d*) *Class C.* A class C amplifier is operated so that the grid bias is considerably greater than that required for cut-off. The plate current is zero when no alternating grid voltage is applied and it flows for appreciably less than one-half of each cycle when an a-c signal voltage is applied to the grid. While distortion occurring in class AB and class B amplifiers can be overcome by using two tubes in a push-pull circuit, this is not possible for a class C amplifier. Class C amplifiers are used primarily as radio-frequency power amplifiers, where the distortion can be overcome with a tuned tank circuit.

c. Tube Characteristics.

(1) The relationships between grid voltage, plate current, and plate voltage in a triode are called tube characteristics. They are, to a large degree, determined by the physical construction of the tube. A

graph obtained by plotting the effect of changing any two of these three quantities on any other, while holding the third quantity constant, is known as a characteristic curve. This curve is usually a static characteristic curve which is obtained with no load in the plate circuit. For the triode the most important of these is a set of curves showing the relation between plate voltage and plate current for different fixed grid voltages (fig. 31).

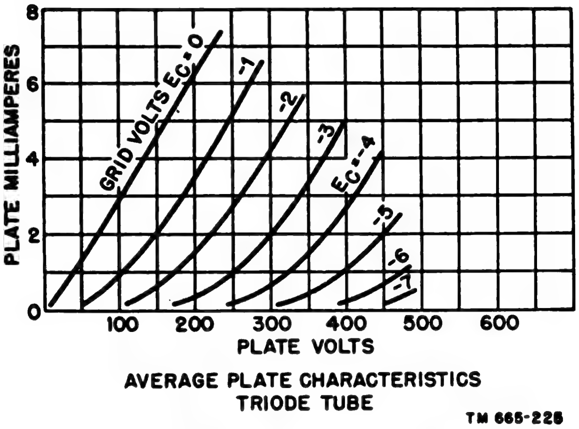


Figure 31. Triode plate-current, plate-voltage characteristics.

(2) The amplification factor, symbolized by the Greek letter μ (mu), is defined for the triode as the ratio of a small plate-voltage change, Δe_b, to the small grid-voltage change, Δe_c, that produced it, the plate current being held constant. In obtaining the amplification factor by measurement or from the characteristic curve, a plate voltage is selected and the grid voltage is adjusted to operate the tube at a particular plate current. The plate voltage then is increased by a small amount and the grid voltage is made more negative by a sufficient amount to keep the plate current constant. Mathematically, this is expressed as

$$\mu=-\frac{\Delta e_b}{\Delta e_c}(i_b \text{ constant})$$

where the minus sign indicates that the changes in plate voltage and grid voltage are in opposite directions. The amplification factors of triodes range from about 3 to about 100.

(3) The *plate resistance*, r_p, is the resistance of the path between cathode and plate to the flow of alternating current. For a fixed grid voltage, the plate resistance is the ratio of a small change in plate voltage to the corresponding small plate-current change, and is expressed in ohms. Mathematically, plate resistance can be expressed as

$$r_p=\frac{\Delta e_b}{\Delta i_b}(e_c \text{ constant})$$

where e_b is in volts and i_b is in amperes.

(4) The *transconductance*, g_m, of a tube takes into account both the amplification factor and the plate resistance, and is the quotient of the first divided by the second. By performing the division, it is seen that transconductance can be defined also as the ratio of a small plate-current change to the grid-voltage change producing it, with the plate voltage held constant. This ratio has the form of a conductance (I/E) and is expressed in *mhos*. In practice, a smaller unit is used. This is the μhmo (micromho) and is equal to one-millionth of a mho. By indicating the ratio of μ to r_p in one term, transconductance serves as a measure of the design merit of amplifier tubes. Its value ranges from a few hundred to several thousand micromhos. In mathematical form, transconductance is

$$g_m=\frac{\Delta i_b}{\Delta e_c}(e_b \text{ constant})$$

If i_b is in amperes and e_c in volts, then g_m is in mhos. This must be multiplied by 1,000,000 in order to convert to micromhos.

d. Polarity Inversion. The sum of the voltage effective at the plate and the voltage across the load must at all times equal the plate-supply voltage, by Kirchhoff's second law. Hence, during the positive half-cycle of an a-c grid signal, both the plate current and the voltage drop across the load resistor increase. As a result, the plate voltage is reduced. Similarly, when the grid voltage swings into the negative half-cycle, the plate current and the voltage drop across the load are reduced. This leaves a greater part of the supply voltage across the tube; that is, the voltage at the plate is increased for a negative grid-voltage swing. Whenever the grid voltage increases (in a positive direction), the plate voltage decreases (in a negative direction), and vice versa. This 180° out-of-phase relationship between the grid signal voltage and the alternating component of the plate voltage (the amplified signal) is called *polarity inversion.*

e. Distortion. An amplified output signal is undistorted if it has the same waveshape as the original grid signal. If the operating point is on the straight-line portion of the characteristic curve of the tube, and if the maximum swings of the grid signal voltage do not drive the tube into any curved portion of the characteristic, the output waveshape is undistorted. For all other conditions, distortion occurs. The extent of the distortion depends partially on the biasing point of the tube.

f. Interelectrode Capacitance. Any two pieces of metal separated by a dielectric have a capacitance between them. The electrodes of a tube are no exception. The capacitance between the electrodes of a tube is called interelectrode capacitance. In triodes, there exists a grid-to-cathode capacitance, a grid-to-plate capacitance, and a plate-to-cathode capacitance. At the high frequencies, the grid-to-plate capacitance can feed back some of the voltage in phase with the grid voltage and thus cause undesirable oscillations.

g. Equivalent Circuit. Many times it is necessary to calculate only the varying (a-c) components of current and voltage in a vacuum-tube circuit. This can be done by using, instead of the actual circuit shown in A of figure 32, an equivalent circuit, shown in B. The variations produced in the plate current of a triode by the application of a signal voltage, e_g, on the grid are exactly the same as would be produced by a generator developing a voltage $-\mu e_g$ and having an internal resistance equal to the plate resistance r_p. This acts in a circuit having a load impedance, Z_L, in series with the plate resistance. The minus sign in $-\mu e_g$ indicates the polarity inversion between grid and plate circuits. By Ohm's law, the plate current in the equivalent circuit is then

$$i_p = \frac{-\mu e_g}{r_p + Z_L}$$

Further, the a-c component of the plate voltage, or the voltage across the load, is

$$e_p = i_p Z_L = \frac{-\mu e_g Z_L}{r_p + Z_L}$$

The ratio of the output voltage, e_p, to the input grid voltage, e_g, is the voltage amplification. This is expressed as follows,

$$\text{voltage amplification} = \frac{e_p}{e_g} = \frac{-\mu Z_L}{r_p + Z_L}$$

From this equation it is seen that the voltage amplification of a triode stage is always less than μ for any finite value of the load impedance.

h. Coupling Methods.

(1) The output voltage of a tube is either utilized by the final load or is applied to the grid of another tube for further amplification. Only the varying or a-c component of the plate voltage is needed for this purpose, and the d-c plate voltage is blocked from the grid of the following stage. Three different types of *coupling* methods are in common use (fig. 33). These are resistance coupling, shown in A, impedance coupling, in B, and transformer coupling, in C.

(2) In the *resistance-capacitance-coupled* circuit, in A, the a-c voltage developed across the plate-load resistor, R_L, is

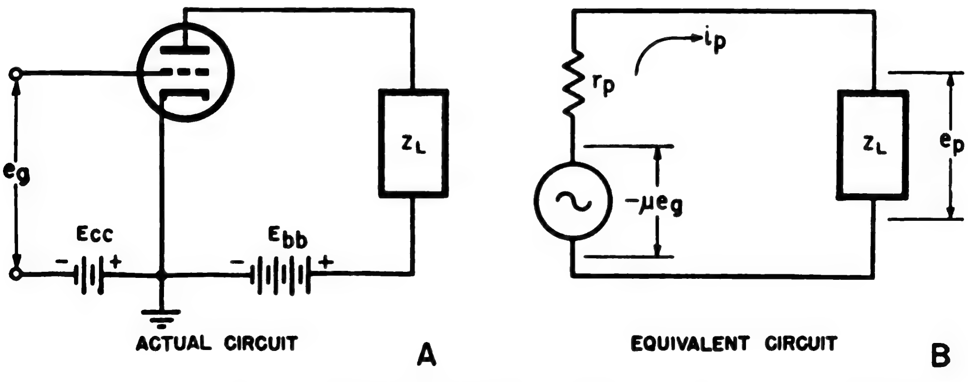
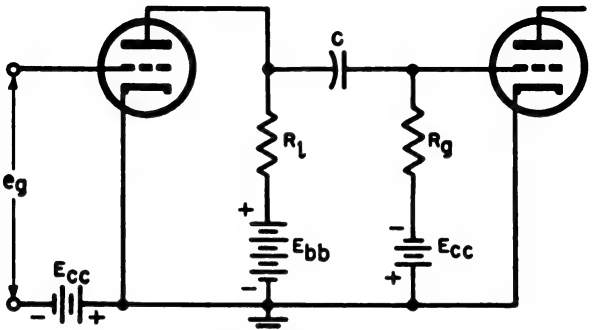
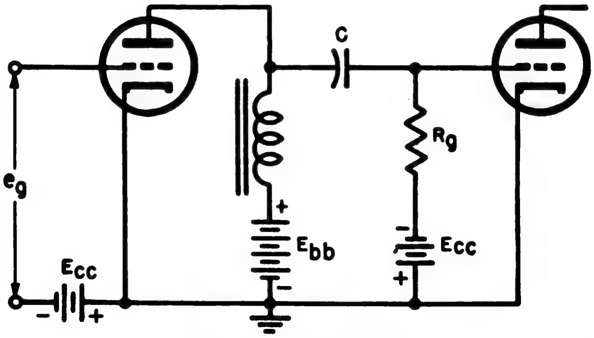


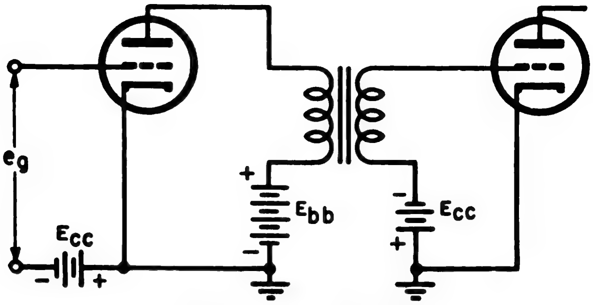
Figure 32. Equivalent circuit of triode amplifier.



RESISTANCE COUPLING A



IMPEDANCE COUPLING B



TRANSFORMER COUPLING C

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Figure 33. Basic coupling methods.

applied to the grid resistor, R_g, of the following tube through the blocking or coupling *capacitor*, C. The blocking capacitor prevents the positive d-c plate voltage of the first tube from reaching the grid of the second tube. Grid resistor R_g provides a resistance across which the input signal to the second tube is developed and also acts as a grid return for the bias. The grid resistor must be sufficiently large not to shunt the plate load appreciably.

(3) In the *impedance-coupled circuit*, in B, an inductor is substituted for the plate resistor. Since the inductive reactance of this coil is high and its d-c resistance low, a high value of a-c load impedance is obtained without an excessive d-c voltage drop, as with resistance coupling. In every other respect the impedance-coupled circuit is identical to the resistance-coupled circuit.

(4) The *transformer-coupled circuit*, in C, utilizes a transformer to couple two amplifier tubes. The primary winding is connected in the plate circuit of the first tube and the secondary to the grid circuit of the following tube. Since there is no direct connection between the two windings, the plate circuit of the first tube is isolated from the grid circuit of the second tube. As in impedance coupling, the primary of the transformer has a high reactance and a low d-c resistance, and thus wastes little of the d-c supply voltage. In addition, transformer coupling has the advantage that the output voltage may be stepped up by the ratio of the secondary turns to the primary turns. The advantages of transformer and impedance coupling are offset to some degree by the simplicity, economy, and generally better frequency response of resistance-capacitance coupling.

24. Tetrode

The tetrode or screen-grid tube is a vacuum tube with four electrodes, a cathode, a plate, and two grids between plate and cathode. The control grid is near the cathode and corresponds to the grid of the triode. The screen grid is mounted between control grid and plate.

a. Operation of Screen. When maintained at a constant potential, the screen grid acts as an electrostatic shield between plate and control grid, and also between plate and cathode. The shielding action of the screen grid results in a greatly reduced grid-to-plate capacitance. This eliminates almost completely the undesirable coupling (feedback) between plate and grid circuits at radio frequencies, which ordinarily makes triodes unsuitable as r-f amplifiers. Another result of the shielding effect of the screen grid is that a change in plate voltage has very little effect on the plate current. Consequently, the plate resistance (defined as the ratio of a change in plate voltage to a corresponding change in plate current) is greatly increased over that of a triode. The effect of the control grid on the plate current is just as great as in a triode. As a result, the amplification factor of a tetrode also is greatly increased over that of a triode.

b. Characteristic Curve. The most useful characteristic curve of a tetrode is the $i_b - e_b$ characteristic for various control-grid voltages and a fixed screen-grid voltage (fig. 34). As positive voltage is applied to the screen grid, the electrons attracted by the screen acquire a high velocity and pass through the screen and on to the plate. The shape of the characteristic curve at low values of plate voltage requires explanation. For fixed control- and screen-grid voltages and for zero plate voltage, all the emitted electrons go to the positive screen grid; hence, the screen-grid current, i_{sc}, is a maximum and the plate current, i_p, is zero. As the plate voltage is increased slightly, the plate attracts some of the electrons passing through the screen grid, and the latter collects fewer electrons. Consequently, the plate current increases and the screen current decreases. As the plate voltage is further increased, electrons strike the plate with such force that other electrons are knocked off the plate into the space between the plate and screen. This effect is known as secondary emission. Since the screen grid is at a higher potential than the plate, these secondary electrons flow to the screen, in a direction opposite to the plate current. The screen-grid current, i_{sc}, therefore increases. The net plate current, is the number of primary electrons received minus the number of secondary electrons lost to the screen grid. If, as a result of the reverse current, more secondary electrons are lost than the number of primary electrons received, then the net plate current can actually become negative. The plate current continues to decrease with increasing plate voltage, since more secondary electrons are produced and lost to the screen grid. The region in which the plate current decreases with an increase in plate voltage is said to exhibit *negative resistance*, and is indicated by the downward slope of the $i_b - e_b$ curve. As the plate voltage is increased beyond this region and approaches the screen-grid voltage, the plate collects practically all the electrons, and the screen current drops to a low value.

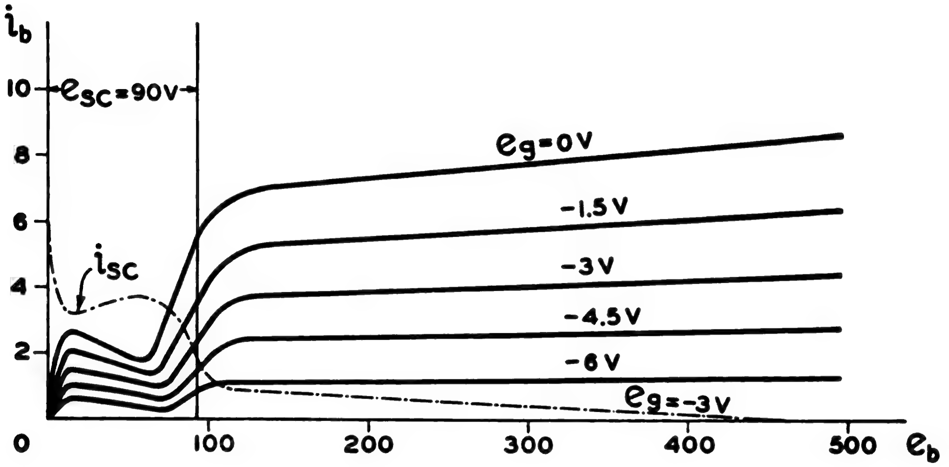

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Figure 34. Typical plate-current plate-voltage tetrode characteristics.

25. Pentode

The pentode is a five-element vacuum tube. The five electrodes are cathode, control grid, screen grid, suppressor grid, and plate. Examples of receiving pentodes are shown in figure 35.

a. Operation of Suppressor Grid. The insertion of a suppressor grid between plate and screen grid of a tetrode overcomes the effect of secondary emission from the plate. The suppressor grid usually is connected directly to the cathode, and therefore, has a negative potential with respect

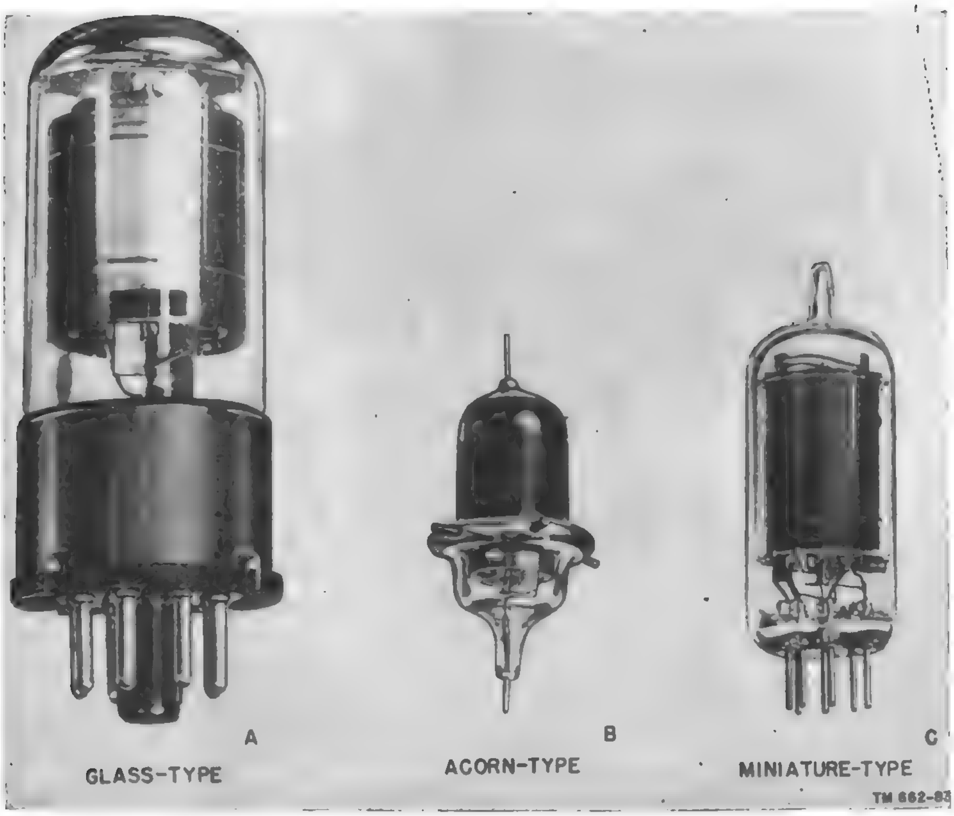

Figure 35. Receiving pentodes.

to the plate. Consequently, it repels the secondary electrons and drives them back to the plate.

b. Variable-Mu Tube. In an ordinary tube the plate current cuts off abruptly when the cut-off bias is reached. This is known as a sharp-cut-off characteristic (fig. 36). In variable-mu or remote cut-off tubes, the design is modified in such a way as to cause the plate current of the tube to decrease gradually at very negative control-grid voltages as indicated by the curve. Such a characteristic is obtained by using a nonuniform control-grid structure. Usually, the pitch of the grid winding is varied, which results in a varying amplification factor for different conditions of operation. As the negative bias is increased the amplification factor of the tube is considerably reduced. Variable-μ tubes are used whenever the amplification of a tube is to be controlled by varying the grid bias. This is the usual method of gain control in r-f amplifiers. Because of the small curvature of variable-mu tube characteristic curves, little distortion is produced capacitively.

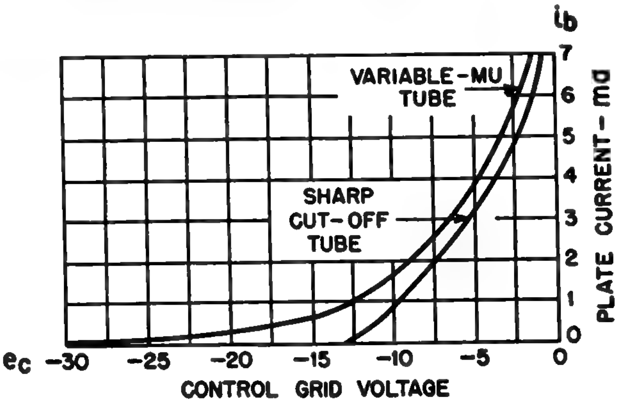

Figure 36. Variable-mu characteristic compared to sharp cut-off characteristic.

c. Use. Because they permit high voltage amplification at moderate values of plate voltage, pentodes are used extensively in receivers as radio-frequency, intermediate-frequency, and audio-frequency voltage amplifiers. They also find frequent use as power output tubes because of their relatively high power output with low grid-driving voltages. However, the distortion produced is somewhat greater than with triodes.

d. Equivalent Circuit. In figure 37, the equivalent circuit, B, of the simple pentode amplifier circuit, A, is known as the constant-current gen-

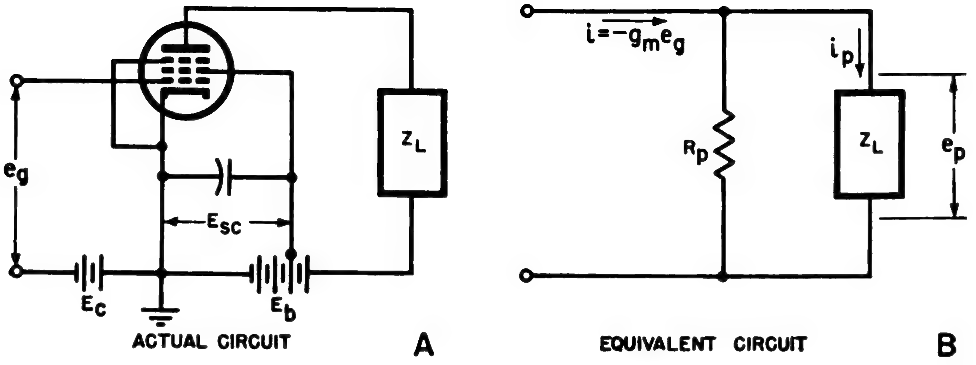

Figure 37. Equivalent circuit of pentode amplifier.

erator form, and it leads to the same results as the constant-voltage generator form shown previously for the triode amplifier. The constant-current generator form is more convenient for pentode calculations. In the equivalent circuit, the effect of applying a signal voltage, e_g, to the control grid is the same as though the tube generated a current, $-g_m e_g$, flowing from the plate toward the cathode through an impedance formed by the plate resistance in parallel with the load impedance. This results in a load current which is

$$i_p = -gm\ e_g \times \frac{r_p}{r_p + Z_L}$$

and a voltage across the load which is

$$e_p = i_p Z_L = -gm\ e_g \times \frac{r_p Z_L}{r_p + Z_L}$$

If μ/r_p is substituted for g_m in these expressions, the same equations are obtained as for the constant-voltage equivalent circuit discussed previously.

26. Beam Power Tube

A beam power tube, (fig. 38) is a tetrode that functions in the manner of a power pentode or a pentode in which directed electron beams are utilized to increase substantially the power sensitivity over that of ordinary tubes. The grids in a beam power tube are so constructed and alined as to form the electrons into concentrated sheets or beams. In tetrodes, additional beam-confining or beam-forming electrodes assist in achieving the desired effect. Secondary emission in beam power tubes is suppressed by the spacing and special shaping of the electrodes. As a result of these design features, large plate currents can be drawn at relatively low plate voltages. Beam power tubes are used as radio-frequency power amplifiers and oscillators, and also as audio-frequency power amplifiers.

27. Multigrid Tubes

To serve special needs, vacuum tubes have been developed with more than three grids; among these are the *hexode* with four grids, the *heptode* with five grids, and the *octode* with six grids. Heptodes are known also as pentagrid converters when they are used as combined mixers and oscillators in superheterodyne receivers. Multigrid tubes frequently are used in electronic gain-control circuits for volume expander and compressor applications.

28. Multiunit Tubes

Multiunit tubes combine the electrode structures of two or more tubes in one envelope, and so are capable of fulfilling the functions of several tubes in one compact unit. Among the simpler types are duplex-diodes and duplex-triodes. Duplex-diodes are used extensively as full-wave rectifiers, detectors, and voltage doublers. Duplex-triodes have many applications, such as combined r-f power amplifier and oscillator, push-pull amplifiers, or phase inverters. More complex multiunit tubes include duplex-diode-triodes (two diodes and a triode), duplex-diode-pentodes, diode-pentodes (a diode and a pentode), triode-pentodes, twin-pentodes, diode-triode-pentodes, and others. These types have a great many applications all of which cannot be listed here. A few examples will illustrate their use. Duplex-diode-triodes and duplex-diode-pentodes are used extensively as combined detector, amplifier, and avc tubes in radio receivers. Diode pentodes find

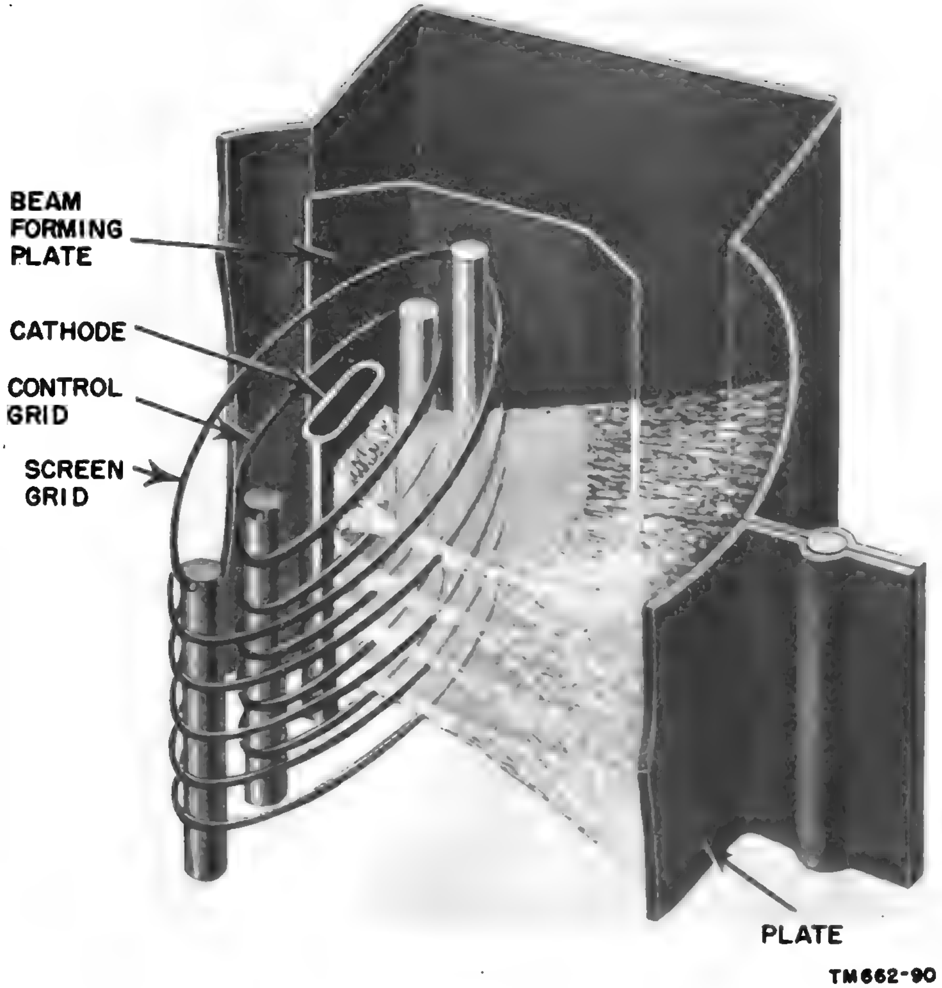

Figure 38. Beam power tube.

application as combined r-f, i-f (intermediate-frequency), or a-f amplifier and detector, and twin pentodes are used in push-pull power output stages.

29. Gas-Filled Tubes

Unlike high-vacuum tubes, which are evacuated as much as possible, gas-filled tubes contain small amounts of gas, such as nitrogen, neon, argon, or mercury vapor. They can have unheated (cold) cathodes or heated (hot) electron-emitting cathodes. In either case, they are capable of conducting substantially higher currents than are the high-vacuum types. They also present a lower impedance to an external circuit and have a smaller voltage drop across them. The large electron current results from the *ionization* of the gas contained within the tube.

a. Operation.

(1) At a certain critical plate voltage, called the ionization potential or firing point, the electrons emitted from the cathode gain sufficient energy to dislodge other electrons from the outer atomic orbits of gas molecules with which they collide. This action is called *ionization.* These dislodged electrons join the emitted electrons and cumulatively ionize all the gas in the tube, thus producing a large current through it.

(2) In cold-cathode tubes, ionization is produced by the attraction of the plate to free electrons within the gas. This takes place, however, at considerately higher plate voltages than for the hot-cathode tubes. Once started, the action maintains

itself. Only if the plate voltage is reduced below a minimum value, known as the extinction potential, does the tube stop conducting. Therefore, a gas tube can be used as a switch. The tube does not conduct if the polarity of the plate voltage is reversed, and it is, therefore, also useful as a rectifier.

(3) If a gas is introduced into a triode, the grid voltage can be used to control the firing potential, and the tube then is called a thyratron. For a given plate voltage, the grid voltage of a thyratron retains control of the plate current below a certain critical negative grid bias. If the grid bias is made more positive than this value, ionization starts, the tube conducts, and the grid loses control. Since the current can be stopped only by removing the plate voltage, the grid voltage serves as a trigger. The critical grid voltage becomes more negative as the plate voltage of the thyratron is increased. Consequently, a wide variety of conditions and firing points can be realized.

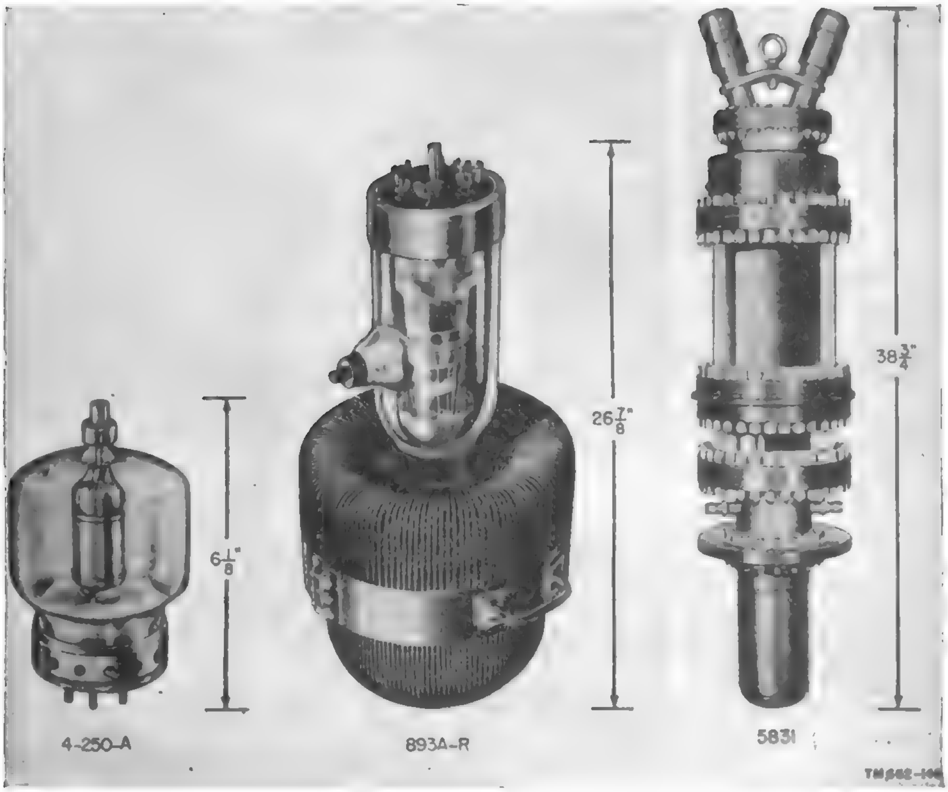

Figure 39. Three typical transmitter tubes.

b. Use. Because of their characteristics, gas-filled tubes are adaptable to a large number of applications in power and control circuits. They are useful also in voltage-regulating circuits and as switching devices in either high- or low-power applications.

30. Transmitter Tubes

Except for some special types, transmitting tubes (fig. 39) are similar to receiving tubes and follow the same operating principles. Diodes, triodes, tetrodes, and pentodes are used also in transmitters, except that the electrodes, supporting elements, and tube envelopes are frequently of larger size in order to handle the greater amounts of power required in transmitters. Tubes of simple design, such as triodes, are preferred over multigrid tubes. Multiunit tubes are used also. Glass envelopes are used to a greater extent in transmitter tubes than in receiving tubes. Because of the greater powers to be dissipated, transmitting tubes are constructed of materials with higher melting points.

a. Operation. In low-power transmitting tubes cooling is achieved in the same manner as in receiving tubes—that is, by conduction through the mounting rods to the stem and by direct radiation. In medium-power and some high-power transmitting tubes, however, air cooling sometimes is provided by means of cooling fins which radiate the heat. Forced air cooling with fans and blowers also may be provided, and, in high-power tubes, circulating water cooling is used frequently.

b. Types and Application.

(1) Large sized diodes, triodes, tetrodes, and pentodes make up the bulk of ordinary transmitting tubes. They may be used, as are conventional receivers, as half- and full-wave rectifiers, class A, B, and C amplifiers, oscillators, and also as frequency multipliers and modulators. Triodes, tetrodes, and pentodes are used in a variety of variable-frequency and crystal-oscillator circuits. Tetrodes or pentodes are required for electron-coupled oscillators, which combine the functions of an oscillator and amplifier. R-f power amplifiers for telegraphy and telephony generally use triodes, tetrodes, or pentodes in class C amplifier circuits to obtain high efficiency. Push-pull class A and class B audio power amplifiers are used as modulators to modulate the r-f carrier with the speech frequencies.

(2) Since, for good stability, most oscillators are operated at relatively low frequencies, it becomes necessary to provide one or more frequency multipliers to obtain the desired output frequency. These are r-f amplifiers which deliver an output at a multiple of the exciting frequency. By tuning the output tank circuit to a harmonic of the exciting frequency, a multiplication can be obtained.

(3) In radar and other applications, frequencies of more than 30,000 mc may be used. Conventional tube types, however, cannot be used above 500 mc. This has led to the development of entirely new types of tubes based on different principles. Among these are the klystrons, which utilize the velocity-modulation principle to function as oscillators, amplifiers, and frequency multipliers. Magnetrons make use of magnetic and electrostatic fields at right angles to each other to provide powerful oscillations in wavelengths as short as 1 centimeter.

CHAPTER 3

RADIO-FREQUENCY GENERATION

31. General

a. Development.

(1) The rapid alternating motion of electrons in a conductor results in radiation of electromagnetic waves, and this phenomenon forms the basis of all radio communication. It is the purpose of electron-tube oscillators to generate these rapidly alternating electron currents from a direct-current supply. When Heinrich Hertz devised the first radio transmitter in 1887, he utilized an electric spark in a tuned circuit to produce very rapid electron oscillations and, consequently, radio waves. Later, the Poulsen electro-arc oscillator and the Fessenden-Alexanderson high-frequency electric generator were developed. Although these devices eventually attained efficiency, they were noisy, had poor frequency stability, and usually produced several radio frequencies in addition to the one desired.

(2) The invention of the De Forest audion triode in 1907 finally made possible the development of powerful transmitting oscillators in their present form, with their excellent frequency stability, silent operation, and ease in changing frequencies. Because of these improvements, electron-tube oscillators are the most widely used generators of radio frequencies, and they are the only ones discussed in this chapter. The basic principles underlying all oscillating systems can be visualized most clearly by considering a mechanical oscillator.

b. Mechanical Oscillator.

(1) A of figure 40, shows a simple spring oscillator, consisting of a weight suspended from one end of a coiled spring. If the weight is pulled downward from its resting position and then released, as in B, it will move back beyond its original position to that shown in C. It then will continue to oscillate up and down until it gradually comes to rest. It stops when all of the energy initially imparted to it is dissipated in heat because of the friction in the spring and bearings. One oscillation or *cycle* is completed when the weight has moved from its initial position, shown in A, down to the position in B, then up to the position in C, and finally back to its original position. The *frequency*, *f*, is the number of oscillations or cyles completed in 1 second. The *period* is the time required to complete one oscillation, and is equal to 1/*f*, the reciprocal of the frequency. It is easily confirmed that it takes exactly the same time for each cycle to be completed, regardless of whether the weight moves through large or small distances in respect to its original position.

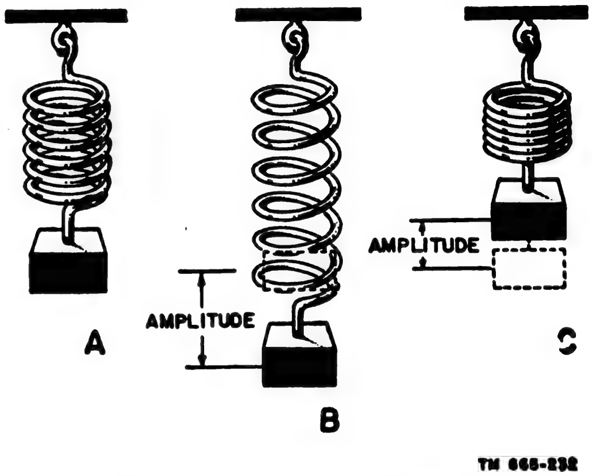

Figure 40. Simple spring oscillator.

(2) The maximum distance the weight moves from its original point, either up or down, is called the *amplitude*. The amplitude of the spring oscillator becomes progressively smaller as time goes on. Finally, the oscillations die down, and the weight comes to a stop. It is possible to obtain an accurate record of the action by attaching a pen to the weight and drawing a paper tape horizontally past the oscillator, in a slow and even motion. The result is a graph of the displacements of the weight from its original position (the axis) against time (fig. 41). Since the oscillations eventually die down, the waveform is called *damped oscillation*.

(3) An analysis of the action described above discloses that two elements are required for oscillations to occur—the spring and the weight. Neither a weightless spring nor the weight alone can produce an oscillation. When the spring is extended by pulling the weight down, potential energy is stored in it in the form of tension. When the weight is let go, this tension or energy is released. The spring pulls back the weight and assumes its original slack position. During the motion, the potential energy of the spring has been transformed into the kinetic energy of motion of the weight. Because of its inertia or flywheel effect, the weight resists any sudden change in its motion. It does not stop, therefore, when the spring is slack again, but continues to compress the spring until all its kinetic energy is again stored as potential energy in the compressed spring. Now, the spring releases its potential energy again in the form of kinetic energy of motion of the weight, and the process is repeated. The action would continue indefinitely if it were not for the fact that some energy is lost as heat because of friction in the spring and bearings and wind resistance. As a result, a little less energy is stored in the spring during each cycle, until the oscillations finally die out.

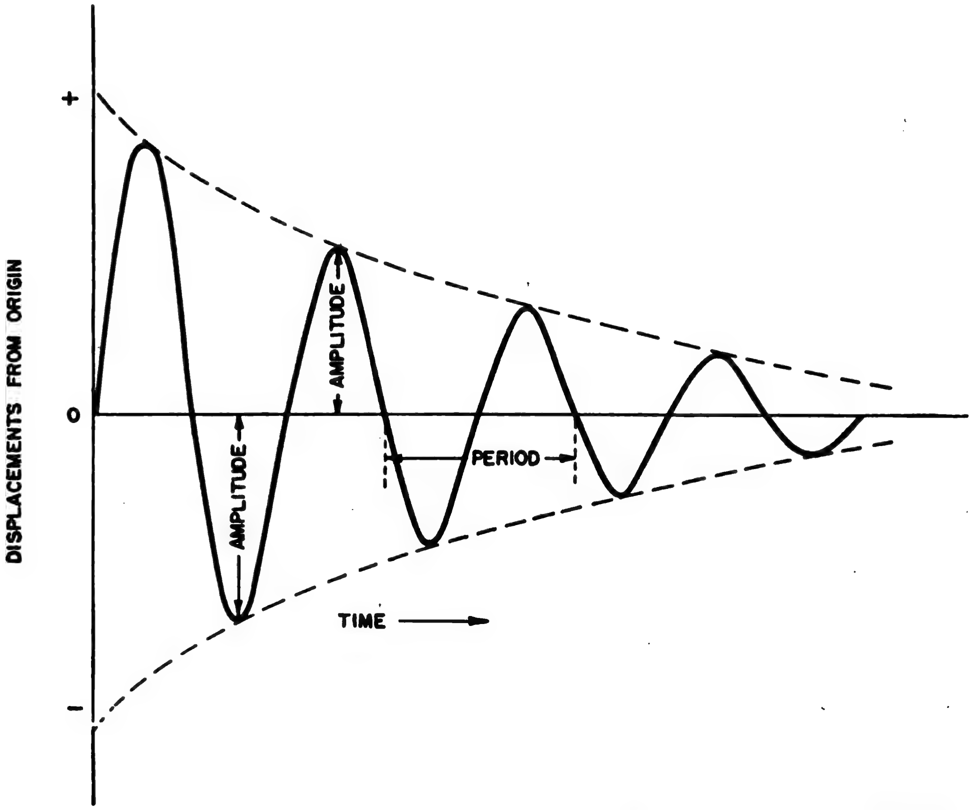

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Figure 41. Waveform of damped oscillations.

(4) If the weight of the spring pendulum is increased, the oscillations take place more slowly, and if the weight is decreased, the oscillations occur at a more rapid rate. In other words, the frequency of oscillations is *related inversely* to the weight. If, on the other hand, the spring is shortened, the oscillations take place at a more rapid rate, and if it is elongated, the oscillations will be slower. Consequently, the frequency also is inversely related to the length of the spring. Instead of lengthening the spring, a more elastic spring can be substituted, and instead of shortening it, a stiffer spring can be used. The frequency of oscillation is inversely related to the elasticity of the spring.

(5) The explanation above is applicable in general for all oscillators, whether mechanical or electrical. *Every oscillating system must have two elements, inertia and elasticity, which can store and release energy from one element to the other at a natural frequency determined by the dimensions of the elements.* In one form or another, inertia and elasticity are present in every oscillating system, and, given an initial impulse, they are sufficient to produce damped oscillations of the type described.

(6) Many oscillators, such as the balance wheel of an ordinary watch or a radio-frequency generator, must be capable of producing continuous, undamped oscillations (fig. 42). In the spring oscillator, this can be accomplished by pulling the weight each time it reaches the bottom limit of its movement by a sufficient amount to overcome the losses caused by friction. If the same result is to be achieved automatically, a mechanical source of energy must be supplied, with some sort of synchronous trigger mechanism which will release the energy to pull the weight at the moment it reaches the bottom limit. This principle is true for all oscillators producing continuous oscillations. An excellent example of a continuous mechanical oscillator is seen in an ordinary clock or watch. Here, the balance wheel and hair spring provide the inertia and elasticity, respectively, of the oscillating system. The main spring is the source of energy, and the escapement is designed to release energy from the main spring at the proper instant during each oscillation of the balance wheel. It will become apparent in later sections of the chapter that an electron-tube oscillator, producing a continuous, undamped output, contains elements exactly analogous to those of a mechanical oscillator.

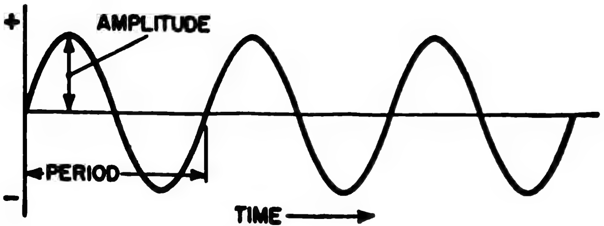

Figure 42. Waveform of undamped oscillations.

(7) Oscillators with a continuous output take energy from a unidirectional (d-c) source and transform it into undamped oscillations. An electrical oscillator, therefore, acts as an energy converter which changes d-c energy into a-c energy. Because of their ability to amplify, electron tubes are very efficient energy converters, and for this reason are universally used as electrical oscillators. If the damped oscillations occurring in a tank, or resonant, L-C circuit are applied to the grid of a triode, the plate current of the tube varies in accordance with the grid signal. This results in an amplified reproduction of the oscillations. Because of this amplification, more energy is available in the plate circuit than in the grid circuit. If part of this plate-circuit energy could be fed back by some means to the grid circuit in the proper phase to aid the oscillations of the tank, its losses would be overcome, and sustained, undamped oscillations would take place. This is, in fact, accomplished by the *feedback circuit*, which permits the combination of a triode and a tank circuit to function as a continuous self-sustaining oscillator.

(8) Since the greater part of this chapter will be devoted to a discussion of elec-

tron-tube oscillators, the basic components and conditions required in every oscillator will be summarized here. To produce oscillations, the following elements must be present:

(*a*) An oscillatory tank circuit, containing *L* and *C*, to determine the frequency of oscillation.

(*b*) A source of (d-c) energy to replenish losses of the oscillator because of resistance or frictional forces.

(*c*) A feedback circuit for supplying energy from the source in the right phase (timing) to aid the oscillations. This process is called *regenerative* feedback. An electron tube can function as an oscillator if it has sufficient amplification and if a sufficient amount of energy is fed back to the tank circuit to overcome all circuit losses. If the losses in the plate and the tank circuits are overcome completely, the effective circuit resistance is zero, and oscillations take place. However, if either the amplification of the tube or the amount of energy fed back is insufficient to overcome the circuit losses and make the effective resistance zero, the circuit will not oscillate. Both conditions must be fulfilled for sustained oscillations to occur.

32. Oscillations in Tank Circuit

a. Discharge of Capacitor Through Inductor.

(1) A tank circuit, consisting of a capacitor and an inductor in parallel (fig. 43), is the simplest type of electrical oscillating system. Its action is analogous to that of the simple spring oscillator and, like the latter, it can generate damped oscillations.

(2) To understand this action, assume that the capacitor in *A* of figure 43, has been charged from a d-c voltage source, and then is discharged through the inductor by closing switch *S*. Assume further that plate 2 of the capacitor is initially charged negatively—that is, it has an excess of electrons—and that plate 1 is charged positively, and hence has a deficiency of electrons. Consequently, an electric field exists between plates 1 and 2.

(3) When the switch is closed, electrons move rapidly from plate 2 through inductor *L* to plate 1. As soon as the electron current flows through *L*, a magnetic field begins to be established around the coil. In building up the field, the magnetic flux lines cut across the turns of the coil, and induce a cemf which opposes the increasing current flow. This slows down the rate of flow of electrons from the capacitor. As plate 2 loses its surplus of electrons during discharge, the current tends to die down, but is prevented from doing so by the inductor which now opposes the decrease in current flow. This tends to keep the electrons moving in the same direction. Consequently, plate 2 not only loses its original excess of electrons but gives up additional electrons, resulting in a deficiency, or positive charge on this plate. Simultaneously, an excess of electrons is pushed onto plate 1, so that it acquires a negative charge, as shown in B. The process stops momentarily when all of the energy that was

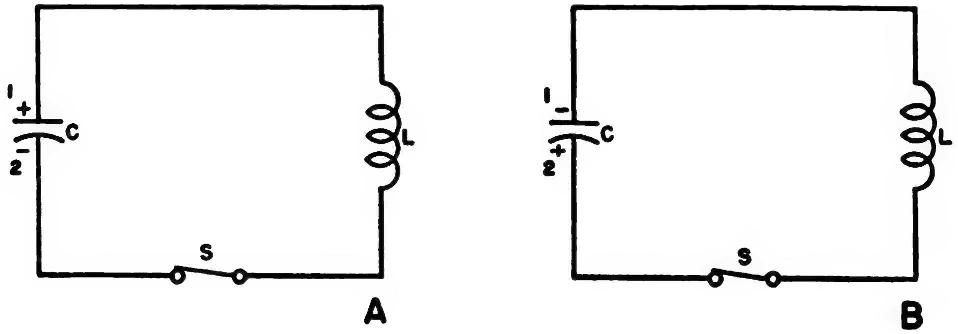

Figure 43. Action of tank circuit.

stored in the magnetic field about the inductor is used up in pushing an excess of electrons to plate 1. At that moment, the magnetic field has completely collapsed, but the energy has been stored again in the electric field of the capacitor, which is now charged in the opposite direction. The action then continues, with electrons moving out of plate 1 through the coil to plate 2. Again, a magnetic field is built up, which stores the energy, and prevents the electron current from dying down. This time, however, the current is flowing in the opposite direction, from 1 to 2, and the flywheel effect of the inductance now pushes an excess of electrons onto plate 2, recharging it negatively. A cycle is completed when the capacitor again is fully charged to the initial polarity.

(4) The sequence of charge and discharge results in an alternating motion of electrons, or an oscillating current. The energy is stored alternately in the electric field of the capacitor and the magnetic field of the inductor. During each cycle, a small part of the originally imparted energy is used up as heat in the resistance of the coil and conductors. The oscillating current eventually dies down when all of the energy used in charging the capacitor has been transformed into heat. The waveform of these damped oscillations is exactly the same as shown in figure 41 for the mechanical oscillator.

b. Mechanical Analogy. The basic principles discussed in paragraph 31 for the mechanical oscillator are involved in the oscillatory discharge of a capacitor through a coil in a tank circuit. This is brought out by a step-by-step comparison between mechanical oscillations in a spring oscillator and electrical oscillations in a tank circuit (fig. 44).

(1) In A, the spring oscillator is completely at rest. This corresponds to the normal uncharged state of the capacitor in the tank circuit, and is indicated by the equal distribution of electrons on both plates.

(2) In B, the weight has been displaced upward from its resting position, thus compressing the spring. The work done in compressing the spring is stored as potential energy in the spring. Similarly, the capacitor has been charged from a d-c voltage source in such a way that plate *Y* has an excess of electrons, or is negative, while plate *X* has a deficiency of electrons, or is positively charged. The electric energy expended in pushing an excess of electrons onto plate *Y* is stored in the electric field of the capacitor.

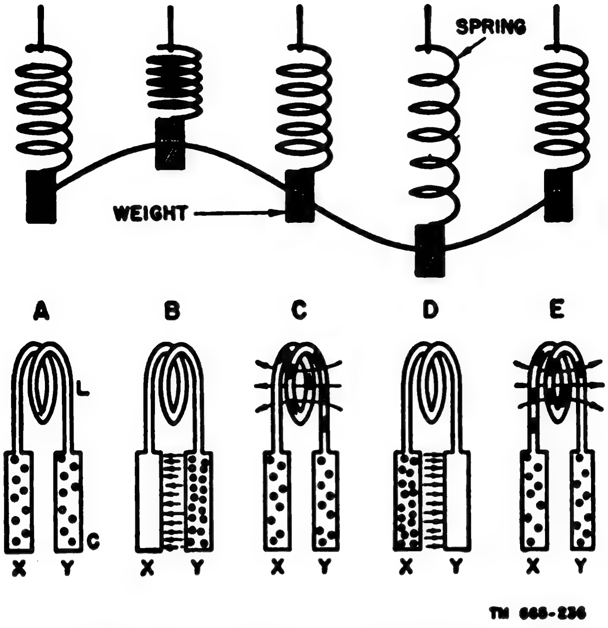

Figure 44. Comparison of mechanical and electrical oscillations.

(3) In C, after having released the weight, the spring has recovered its original length, and the weight is back in its original position. However, because of the flywheel effect, or inertia, the weight continues to swing beyond its original resting position. The potential energy of the spring has been transformed completely into kinetic energy of motion of the weight. Correspondingly, the capacitor is discharging, and an electron current flows from plate *Y* through the coil to plate *X*. A magnetic field is building up around the coil, which stores the energy released by the capacitor. The current and the energy in the magnetic field are greatest at the moment when the capacitor is completely discharged and its electric field disappears. The inertia

effect of the inductance coil, however, prevents the current from dying out at this moment. It continues to flow, recharging the capacitor in the opposite direction.

(4) In D, the weight has reached its lowest point, the spring is extended to its maximum length, and is under tension. The weight is momentarily at rest, and all of the energy is stored in the spring tension. This corresponds to the complete recharging of the capacitor, but now in the opposite direction. The magnetic field has contracted, and all of the energy is stored momentarily in the electric field of the capacitor.

(5) A full cycle is completed in E. The weight has returned to its original position, and the potential energy of the spring again is transformed into the kinetic energy of the weight. Similarly, an electrical cycle has been completed. The capacitor is discharging and the energy of the electric field between the capacitor plates again is stored in the magnetic field around the coil. The wave-form of the oscillations during 1 cycle is illustrated by connecting the midpoints of the weight displacements with a smooth curve.

(6) The foregoing analysis shows that there is an exact parallel between the mechanical and the electrical oscillating systems. The elasticity of the spring is analogous to capacitance, and the inertia of the mass is analogous to the self-inductance of the coil. The similarity between the two actions is so complete that the comparison shown in the accompanying chart can be made.

	Mechanical oscillator (spring)	Electrical oscillator (tank circuit)
Elasticity	Spring	Capacitor.
Inertia	Mass (or weight)	Inductor.
Resistance	Friction	Electrical resistance.
Source of energy	Initial impulse	D-c voltage source.
Amplitude	Maximum displacement of weight or maximum velocity of motion.	Maximum charge on capacitor or peak electron current.
Rate of oscillation	Constant frequency	Constant frequency.
Waveform	Damped oscillations	Damped Oscillations.
Cause of damping	Energy loss in heat due to friction.	Energy loss in heat due to resistance.

c. Frequency.

(1) Since capacitance corresponds to the elasticity of a spring, an increase in capacitance would be expected to lengthen the period of oscillation in a tank circuit, that is, lower its frequency. This is indeed true. As the capacitance is increased, more charge must be transferred in and out of the capacitor during each cycle, and complete discharge or charge will take a longer time. Consequently, the period is lengthened, and the frequency is lowered.

(2) It has been pointed out that the greater the inertia of a mechanical oscillator, the longer the period of each oscillation. Since self-inductance corresponds to inertia, this is true also for the inductor in a tank circuit. The greater the inductance of the coil, the greater is its opposition to any change in current flow, and hence the longer is the time required for completion of each cycle. The greater the value of the inductance, therefore, the longer is the period, or the lower is the frequency of oscillations in the tank circuit.

(3) The frequency of oscillations in a tank circuit is, therefore, inversely related to both inductance and capacitance. The approximate formula for the natural frequency of oscillation is

$$f=\frac{1}{2\pi\sqrt{LC}}$$

where

f = the frequency in cycles per second
L = the inductance in henrys
C = the capacitance in farads

The approximate formula for the natural frequency of oscillation is the same as that for the resonant frequency of tank circuit. It has been shown previously that, for a parallel-resonant circuit at the reasonant frequency, the circulating current in the tank circuit is a maximum, and that the line current is a minimum and just sufficient to overcome the losses occurring in the resistance of the tank circuit. When an a-c voltage is impressed across a tank circuit, these conditions occur at the frequency at which the tank circuit breaks into natural oscillations, and draws just sufficient current from the energy supply (a-c voltage) to overcome its internal losses. This, indeed, is the fundamental meaning of resonance. At the resonant frequency, the external supply releases just sufficient energy with the proper timing to sustain the natural self-oscillations of the tank circuit.

(4) Mechanical objects illustrate the same principle. Every object has its own natural frequency of vibration. For example, when a certain note is struck on a piano, a nearby vase may begin to vibrate. This means that the natural frequency of oscillation of the object has been excited by a piano tone of the same frequency, and energy is being transferred to the vibrating object to sustain oscillations. As another example, soldiers marching across a bridge in step may cause it to vibrate at its natural frequency. If the constant small impulses from the marching soldiers take place at the same frequency as the natural frequency of oscillation, the effect will be cumulative and the amplitude of oscillation can become so large that the bridge may be destroyed.

d. L-C Ratio and Q.

(1) The expression given above for the natural frequency of oscillations of a tank circuit shows that, for any given frequency, there is an infinite number of possible combinations of L and C. The same frequency of oscillation can be produced with a large inductor, L, and a small capacitor, C, or with a small inductor, L, and a large capacitor, C. In practice, however, the choice of the L-C ratio for a particular frequency is restricted because the ultimate performance of the tank circuit depends to a large extent on this ratio.

(2) It has been shown that the impedance of a parallel-resonant tank circuit is equal to L/CR. For a fixed resistance, or Q, therefore, the impedance of the tank circuit varies directly in proportion to the L-C ratio. Since the desired impedance of the tank circuit in a vacuum-tube oscillator is determined to some extent by the operating conditions of the tube, the choice of L-C ratios is limited. Since Q equals X_L/R, the larger the inductance for a given frequency, the higher the inductive reactance, and the higher the Q, if the resistance remains at a constant value.

(3) It has been pointed out also in chapter 2 that the factor Q is a measure of the ratio of the reactive energy stored in the tank circuit to the energy lost in the resistance during each cycle. Expressed mathematically,

$$Q = \frac{2\pi \times \text{energy stored}}{\text{energy lost per cycle}}$$

It has been found in actual experience that tank circuits, having stored in them less than twice as much energy as they dissipate each cycle, tend to operate erratically and are unstable. On the other hand, if the ratio of energy stored to energy lost, and consequently the Q, become too large, operation of the tank circuit is inefficient because of the large amount of circulating power wasted. In the absence of other determining factors, therefore, the ratio of energy stored to energy lost per cycle is made about equal to two. Substituting this value in the expression above, the minimum value of Q should be about $2\pi \times 2$ or 4π (about 12.5). Since, by definition, $Q = \frac{2\pi f L}{R}$, the value of inductor L can be calculated for the Q of 12.5, and fixed frequency and resistance. This limits the value of C for the same frequency of oscillation. It must not be assumed that the preceding expressions determine the value of the L-C ratio rigidly, since other design considerations may be more important in particular cases. Among the most important of these is the effect of *loading* the tank circuit—that is, drawing energy from it. This will be discussed later.

33. Tickler Feedback Oscillator

a. Circuit.

(1) One of the earliest electron-tube circuits to fulfill all of the conditions listed above is the tickler feedback oscillator (fig. 45) devised by Armstrong. This

circuit is known as a *series-fed* oscillator, because the B battery is in series with the feedback coil, *L*. Both the direct and the alternating components of the plate current, therefore, flow through *L*. An alternative version of the tickler feedback oscillator is the *parallel-fed* type. In this circuit, the plate circuit is divided into two parallel branches, one of which carries the direct current and the other the alternating current. Paragraph 34 on the Hartley oscillator includes a detailed discussion of series- and parallel-fed circuits.

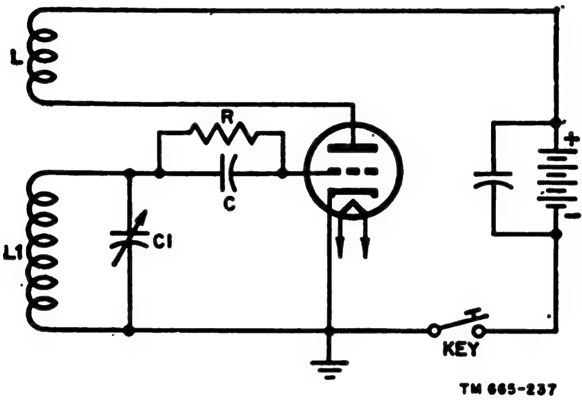

Figure 45. Tickler feedback oscillator.

(2) The oscillatory tank circuit (fig. 45) is made up of *L*1 and *C*1, the source of d-c energy is the plate-supply voltage, *B*, and the *tickler* coil, *L*, and tank coil, *L*1, coupled together, comprise the feedback circuit. The bypass capacitor is placed across the B battery to provide a low-reactance path for the alternating component of the plate current. Resistor *R* in the grid circuit is the grid leak, and its function together with *C* is to furnish a self-adjusting negative bias to the tube. Its operation will be discussed later. The key serves to interrupt the oscillations in accordance with a code, for use in telegraphy transmission.

(3) Once oscillations have been started in the tank circuit, *L*1-*C*1, they appear in amplified form in the plate circuit of the tube. Part of the energy is fed back from tickler coil *L* to tank coil *L*1 by mutual induction, thus overcoming losses and sustaining the oscillations. The tube itself introduces a phase shift of 180° between grid and plate circuit. The combination of *L* and *L*1 constitutes a transformer, and consequently another phase shift of approximately 180° takes place here. As a result, the voltage fed back is in proper phase with the voltage in the grid circuit, and *regenerative* or *positive feedback* takes place.

(4) To understand the action of the circuit, it must be remembered that only a *changing* magnetic field is capable of inducing a voltage in a nearby coil. An expanding magnetic field induces a voltage of one polarity, and a contracting magnetic field induces a voltage of the opposite polarity.

(5) Assume that the cathode of the triode tube is heated and that electrons are being emitted. The moment the key is closed, plate current begins to flow through the tube and through the external, circuit, consisting of tickler coil *L* and the battery. This current sets up an expanding magnetic field around coil *L* and so induces a voltage in tank coil *L*1. Assume that the initial induced voltage is such that the upper end of the *L*1-*C*1 tank circuit is positive. This positive voltage charges capacitor *C*1, and places a positive charge on the grid of the tube, which is connected to the upper end of the tank circuit. Since the grid has no bias initially, this positive charge increases the plate current, and this builds up still further the magnetic field around tickler coil *L*. As a result, a larger positive voltage is induced in *L*1 and placed on the grid, and *C*1 is further charged. Again, the plate current rises and the field of *L* expands, placing a still greater positive voltage on *C*1 and the grid. This process continues until the plate current reaches its saturation point (the point at which a further increase in grid voltage does not increase plate current) and tapers off. Then the field about coil *L* stops expanding and becomes static.

(6) As the magnetic field of coil *L* stops expanding, the voltage induced in *L*1 begins to drop and finally reaches zero. Now, however, capacitor *C*1, which has been

charged to the maximum positive voltage, begins to discharge and then to recharge in the opposite direction. This makes the upper end of the tank circuit $L1$-$C1$ negative. As the potential on the upper end of $L1$-$C1$ is reduced from its positive value to zero and then becomes negative, the voltage on the grid is equally reduced. This lowers the plate current. As the plate current decreases, the field about L starts contracting and induces a negative voltage in $L1$. This leads to a still greater negative grid voltage. As the negative charge on the grid increases, the plate current drops more and more, until finally it is cut off. At this instant, the field about L has collapsed completely, and the voltage induced in $L1$ disappears. Capacitor $C1$ begins to discharge and the negative grid voltage rises toward zero. Since the grid is now less negative (or more positive) than the value it had at cut-off, the plate current increases again, and the entire cycle is repeated.

(7) The entire process just described takes place very quickly, and is repeated thousands of times in an extremely brief period of time at a rate determined by $L1$ and $C1$. Oscillations will not be sustained if the amplification of the tube or the energy fed back by tickler coil L to the tank circuit is insufficient to overcome circuit losses. The amount of energy fed back depends on the mutual inductance, M, between L and $L1$. As the coils are moved farther apart, the coupling between the coils decreases, and at a certain critical value of M, the coupling is too loose to sustain oscillations.

b. Waveform of output. Without feedback, damped oscillations occur in tank circuit $L1$-$C1$ with a waveform as shown in figure 41. If the coupling between L and $L1$ is adjusted so that just enough energy is fed back during each cycle to make up for the losses incurred during that interval, an almost pure sine-wave output can be obtained with a waveform as shown in figure 42. However, if the coupling between L and $L1$ is tight, excessive regeneration (positive feedback) results, and the output waveform becomes distorted (fig. 46). It can be shown that a complex waveform of this type contains, in addition to the fundamental sine-wave frequency, many other frequencies which are multiples of the fundamental frequency; these are called *harmonics.* Usually, only the fundamental frequency of the oscillator is desired, and the harmonics are rejected by additional tuned circuits. In some applications, however, the second or third harmonic (twice or three times the fundamental frequency, respectively) may be desired. In any case, there is considerable latitude in the coupling between the coils and hence the amount of regeneration before noticeable distortion of the output waveform takes place.

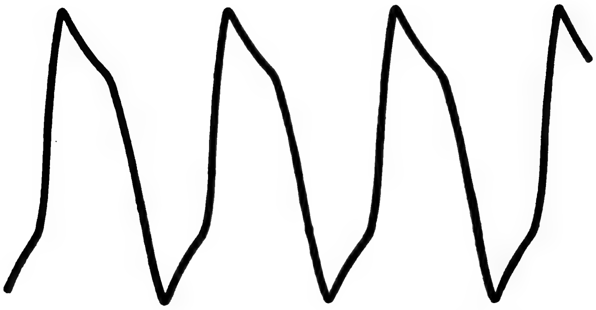

Figure 46. Distorted output waveform caused by excessive feedback.

c. Grid-Leak Biasing of Oscillators.

(1) *Action.* Grid-leak resistor R and grid capacitor C (fig. 45) furnished the negative bias required for operation of the tube. Grid-leak bias is used universally in triode oscillators rather than fixed bias, to insure stable operation and make the oscillator self-starting. Capacitor C is large enough to provide a free (low-reactance) path to the grid for the excitation signal, and thus bypasses high-resistance grid leak R. In operation, the grid is driven positive during postive half-cycles of the oscillations, and therefore draws grid current. The electron current flows from the cathode to the grid and then through the external circuit consisting of R and $L1$. This develops a voltage drop across R. The end of R connected to the grid is made more negative than the other end, and the grid is biased negatively by an amount equal to the voltage drop across R. The voltage present across R during grid-current flow charges capacitor C. If R and C are

are sufficiently large, the charge on C leaks off only very slowly during negative half-cycles when no grid current flows. Hence, for all practical purposes, the voltage across C remains constant throughout a complete cycle, and maintains a steady bias on the tube.

(2) *Time constant.* The rate of discharge from C depends on both the capacitance and the resistance of the grid-leak resistor. The larger the capacitance of C, the greater the charge it can hold, and the longer it will take to discharge completely. Also, the greater the grid-leak resistance, the longer it takes for a capacitor of a given size to discharge through it. The product of R and C is known as the *time constant* of the combination. If the value of the time constant, R times C, in seconds is large compared with the period of one oscillation, the capacitor will hold its charge at an almost constant value. To avoid intermittent operation of the oscillator, however, the time constant should not be too large.

(3) *Class C operation.* If appreciable power is to be produced in the oscillator the value of the grid leak is so adjusted that the grid bias during operation is greater than cut-off, and hence no plate current flows in the absence of an alternating grid voltage. During part of the positive half-cycles, however, the grid voltage becomes less negative than required for cut-off and plate current flows. It will be remembered that this defines class C operation. Since plate current flows for less than one-half of each cycle, the waveform of the plate current is distorted. This distortion is canceled in the tank circuit because of the flywheel effect.

(4) *Self-starting.* If fixed grid bias were used with class C operation, no oscillations could be built up, since the bias is beyond plate-current cut-off. Without plate current, an initial impulse could not be amplified by the tube. The use of grid-leak bias makes the oscillator self-starting, because the grid bias is *initially zero*, which permits plate current flow. Any initial impulse, such as the closing of the key, thermal agitation, or a transient voltage, is amplified and thus starts the building up of oscillations in the manner described before. Small random variations are always present in the circuit to start the oscillations.

(5) *Equilibrium.* As oscillations begin to build up, the grid draws current and is biased negatively because of the grid-leak resistance. This reduces the d-c plate current and the amplification of the tube. Because of the grid leak, the plate current actually never reaches saturation, as was described previously for the initial action. Instead, an equilibrium value of the plate current is reached such that the power generated in the output is just able to sustain the amplitude of oscillations required to produce this power. At this point, no surplus energy remains to build up the amplitude of oscillations further. The self-regulating action of the grid leak, therefore, prevents the unchecked build-up of the oscillations to the maximum emission or saturation value, which might damage the tube.

(6) *Intermittent operation.* The grid leak can maintain this stabilizing action only if the time constant of the R-C combination is of the proper value for the bias to follow sudden changes in the amplitude of oscillations, and hence the average d-c plate current. If the time constant of the capacitor, grid-leak combination is too large, it will take a considerable time for the negative charge to leak off through R, and the bias can adjust itself only very slowly to sudden changes in the amplitude of oscillations. Any slight irregularity tending to reduce the amplitude of oscillations then will cause them to die out in the manner described, since, with the large time constant, the grid bias tends to remain constant. To prevent the dying out of oscillations, the grid bias should, of course, reduce itself automatically. After cessation of oscillations, the grid capacitor gradually discharges through the grid leak, and reduces the bias until the tube again amplifies. Oscillations then will build up again, and the whole process starts over. The intermittent

cycle is repeated at regular intervals, since the plate current never is steady enough to maintain constant output without proper bias regulation.

(7) *Design.* The chief considerations that determine the design of the *R-C* grid-leak combination have been given. The grid capacitor must be large enough to have a low reactance compared to the grid-leak resistance and, in addition, it should be at least 5 to 10 times the grid-to-cathode capacitance of the tube. The grid leak is determined by the value of bias required for class *C* operation and by the amount of grid current drawn by the tube. These values are listed in tube manuals. The time constant of the combination must not be so large as to cause intermittent operation.

34. Hartley Oscillator

A modified version of the tickler feedback circuit, using a tapped coil common to both the plate and the grid circuit rather than two separate coils, is known as the *Hartley oscillator* (fig. 47). Except for minor modifications in the manner in which coupling is obtained between plate and grid circuit, the operation of the Hartley oscillator is identical with that of the tickler feedback oscillator just discussed.

a. Methods of Applying Plate Voltage. Two methods of connecting the plate-supply voltage in the Hartley oscillator—the *series feed* and the *parallel or shunt feed*—are shown in figure 47. These two methods can be applied to practically all triode oscillators. Each has certain advantages and disadvantages which merit a more detailed discussion.

(1) In the series-fed Hartley oscillator, in A, both the d-c plate current and the alternating component of this current flow through coil *L*2 in the common cathode circuit, no other path being available. However, to avoid the high internal resistance of the power supply or B battery, a low-reactance path for r-f is provided in the form of a bypass capacitor across the d-c supply voltage. The a-c component of the plate current, therefore, takes the path of lowest opposition, bypassing the B battery. With very little reactance to r-f, the bypass capacitor effectively places the plate of the tube at ground potential. If the ground in A were placed at the cathode, as is sometimes the case, the plate would not be at r-f ground potential, since part of the tank coil, *L*2, would be located between plate and ground.

(2) In the parallel-fed Hartley oscillator, shown in B, the plate circuit is divided into two parallel branches, one of which carries the direct current and the other the alternating current (r-f). A high-reactance radio-frequency choke coil keeps the alternating current out of the d-c path and a blocking capacitor keeps the direct current out of the a-c path. The d-c plate current, therefore, can flow only in the plate-to-cathode circuit containing the choke coil and B battery, and cannot enter plate-circuit coil *L*2. On the

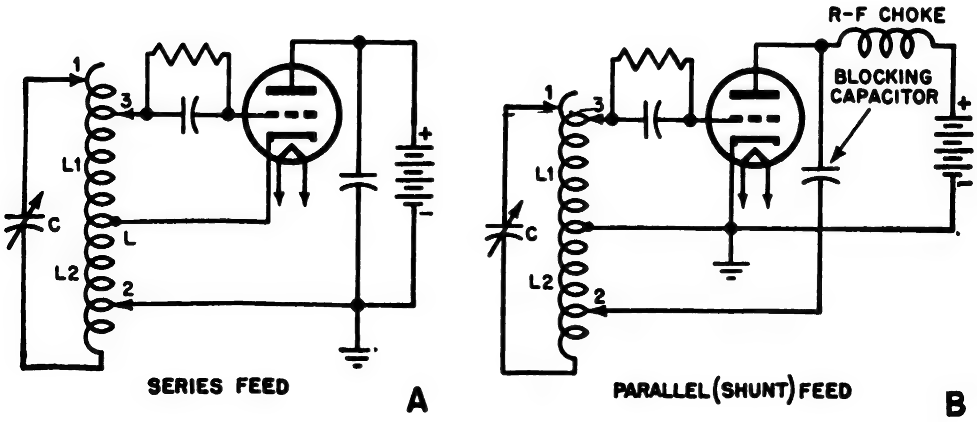

Figure 47. Hartley oscillator.

other hand, the a-c component of the plate current (r-f) cannot flow through the power supply, since the r-f choke offers a very high impedance to the flow of radio-frequency currents. The r-f can flow readily, however, from the plate to the tank circuit, because the blocking capacitor offers negligible opposition to alternating current.

(3) Although both methods have certain advantages, the parallel-fed circuit generally is preferred. The only advantage of the series-fed circuit is that it eliminates the r-f choke coil. Since the choke is effectively in parallel with a portion of the tank circuit, it may be a source of serious loss if it does not present a very high impedance at the frequency of oscillation. For this reason, the choke inductance must be at least 5 to 10 times the inductance of the tank circuit. In addition to inductance, the choke coil has distributed capacitance, and this combination can be resonant at one or more frequencies. If the resonant frequency of the choke should happen to be the same as that of the tank circuit, the choke would absorb an appreciable amount of power. Parasitic (spurious) oscillations can occur at other frequencies. A single choke, therefore, cannot be used over too wide a frequency range of oscillator operation.

(4) The advantage of the parallel-fed circuit and consequent disadvantage of the series-fed circuit is that the former keeps the high-voltage d-c out of the tank coil, thus preventing possible injury to operating personnel. If the cathode of a series-fed oscillator should be grounded, as is sometimes the case, the high d-c voltage between the tank coil and ground would present a serious hazard to anyone accidentally touching the tank coil. Furthermore, the choke prevents r-f energy from entering the power supply and being coupled to other circuits which use the same power supply. A further advantage of the parallel-fed circuit is that the tank circuit components need only be insulated for the r-f present and not for high-voltage d-c as well.

b. Operation.

(1) The Hartley circuit uses only one coil, part of which is in the plate circuit and part in the grid circuit, instead of the two separate coils of the tickler feedback oscillator. The lower portion of the tank coil, *L*2, is inductively coupled to the upper portion, *L*1, the combination functioning as an autotransformer. Since the variable tank capacitor, *C*, is connected across both coil sections, capacitive coupling is present in addition to the coupling by mutual inductance. Adjustable taps sometimes are provided to obtain optimum performance in power oscillators but usually are not found in low-power oscillators.

(2) Tap 1, together with the variable capacitor, *C*, adjusts the frequency of oscillation. Inductance *L* of the tank can be decreased by moving the tap down. The frequency is ½ pi $\sqrt{LC}$, where *L* is the total inductance connected across *C*. Tap 2 adjusts the effective impedance of plate-circuit coil *L*2, and has only a slight effect on frequency. The more turns that are included between cathode and plate, the higher is the plate-circuit impedance. Tap 3 adjusts the grid excitation voltage to the proper value for maximum output. Sufficient excitation must be provided to overcome all losses in the tank and associated plate circuit and hence make the effective circuit resistance zero, as previously explained. At the same time, the excitation must not be so large as to overdrive the oscillator and distort the waveform of the output. The excitation is increased by moving tap 3 upward. All the taps are generally adjusted together, since their setting is interdependent to some degree.

(3) It has been stated previously that an electron tube normally introduces a 180° phase shift between grid and plate voltage. Hence, another phase shift of 180° must be provided in the feedback circuit so that the voltage being fed back is in phase with the initial grid voltage. In this way, the positive feedback (regeneration) required for oscillation takes place.

(4) This phase correction needed for regeneration is obtained in the tank coil. The two opposite ends of autotransformer $L1$-$L2$ are actually 180° out of phase; that is, whenever one end of the transformer winding is positive the other end is negative, and vice versa. A fixed voltage drop across the tuned circuit will appear across the complete coil, made up of $L1$ and $L2$. When viewed from one end, the voltage drop increases progressively along the turns of the coil. When the upper end of L (connected to the grid) is positive, for instance, the lower end is at a minimum potential. However, the tap connected to the cathode is at an intermediate voltage, and so is negative in respect to the upper end and positive in respect to the lower end. Or, viewed from the cathode tap, the upper end of the coil is positive and the lower end is negative. Since the grid and plate are connected to opposite ends of the coil they are, therefore, opposite in polarity or phase. In this way, the feedback is phased properly to sustain oscillations.

35. Colpitts Oscillator

a. Operation. The Colpitts oscillator (fig. 48) is similar to the Hartley circuit just discussed, except that two capacitors, which may be variable, are used in the tank circuit instead of the tapped coil. These capacitors are $C1$ and $C2$. The grid voltage is adjusted by capacitor $C1$, instead of the tap used on the coil in the Hartley circuit. The tank again is common to both the plate and grid circuits, but the feedback is obtained by the relative voltage drops across the two capacitors. Note that this circuit is parallel-fed. Blocking capacitor C_b prevents the d-c plate current from reaching the tank circuit, and the r-f choke keeps the r-f out of the power supply. Grid-leak bias is used, but grid leak R_g is connected in parallel with the grid circuit, rather than in series with it. This is necessary to provide a d-c return path for the grid current. The parallel connection of the grid leak is preferred if the tank coils are to be exchangeable for different frequency bands. Except for these minor modifications, the operation of the Colpitts oscillator is the same as that of the Hartley circuit.

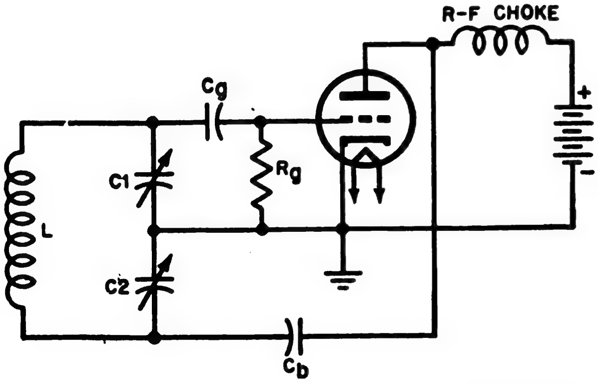

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Figure 48. Colpitts oscillator

b. Feedback.

(1) The two tank-circuit capacitors, $C1$ and $C2$, act as a simple a-c voltage divider. The tap between them fulfills the same purpose as the tapped coil in the Hartley circuit. It assures both the proper amount and the correct phase of the feedback voltage. As seen from the cathode-connected tap, whenever the top plate of $C1$ is positive, the plate-connected plate of $C2$ is negative, or vice versa. Because of this polarity reversal, the correct 180° phase shift is obtained.

(2) As in any a-c voltage divider, the total voltage across $C1$ and $C2$ divides in the ratio of their respective reactances. However, since capacitive reactance varies inversely with the capacitance ($X_C = \frac{1}{2\pi fc}$), the voltages divide as the inverse ratio of the two capacitances. In other words

$$\frac{E_{C1}}{E_{C2}} = \frac{C2}{C1}$$

where

E_{C1} = the voltage drop across $C1$ = a-c voltage across the grid,

E_{C2} = the voltage drop across $C2$ = a-c voltage on plate.

Hence, to increase the voltage across $C1$, and, consequently, the grid excitation, the capacitance of $C1$ must be decreased. To maintain the same oscillation frequency, however, the total capacitance across L must be constant. As a result, whenever $C1$ is decreased, $C2$ must be increased by an amount sufficient to keep the total capacitance, and hence the frequency, the same. If $C1$ is increased to lower the exitation voltage, then $C2$ must be decreased.

c. Frequency. The frequency of oscillations is determined by inductor L and the total capacitance, C_T, in the tank circuit. As before, the expression is

$$f=\frac{1}{2\pi\sqrt{LC_T}}$$

By the formula, the capacitance of two capacitors in series is

$$C_T=\frac{C1\times C2}{C1+C2}$$

Hence, the formula for the resonant frequency becomes

$$f=\frac{1}{2\pi}\sqrt{\frac{C1+C2}{L\times C1\times C2}}$$

36. Meissner Oscillator

a. The circuit of the Meissner oscillator is shown in figure 49. It is similar to the Hartley oscillator, except that the tank circuit, LC, is floating; that is, it is not connected directly to the plate and grid circuits. The tank coil, L, serves as an inductive coupling or link circuit between the plate-circuit coil, L_p, and the grid-circuit coil, L_g. For clarity, a series-fed circuit is shown, although, in practice, a parallel-fed circuit might be preferred.

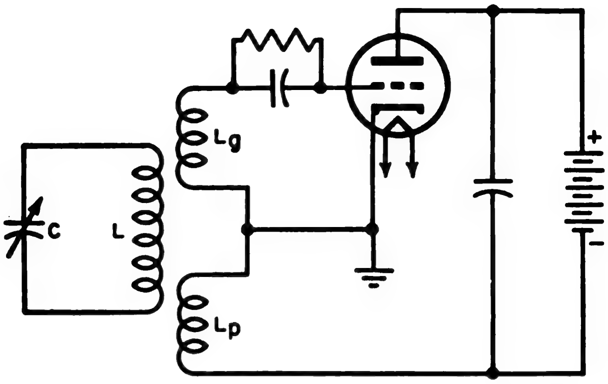

Figure 49. Meissner oscillator.

b. There is no mutual coupling between coils L_p and L_g, except that provided by the tank coil. Energy from the plate circuit, therefore, is passed from L_p to L, thus exciting the tank, and from there it is fed back to grid-circuit coil L_g. Because of the tap between L_p and L_g, the grid and the plate voltage are of opposite polarity in respect to the cathode, as is required for positive feedback.

c. The total mutual inductance between L_p and L_g, coupled through the link coil, L, cannot be made as great as if the coils themselves were coupled. This is so because the coefficient of coupling between air-core coils is considerably less than unity, and since there are two couplings required, the over-all coupling coefficient is less than for any pair of coils. In practice, this does not matter if the tank-circuit coil L has a sufficiently high Q. This condition must also be fulfilled to obtain stable oscillations in the tank circuit.

d. For a high-Q tank circuit, the frequency of oscillations is solely determined by L and C. As before, it is given by

$$F=\frac{1}{2\pi\sqrt{LC}}$$

37. Tuned-Plate Tuned-Grid Oscillator

a. Circuit. The TPTG (tuned-plate tuned-grid) oscillator uses a tuned tank circuit in both the grid and the plate circuits (fig. 50). The two coils, $L1$ and $L2$, are not coupled inductively.

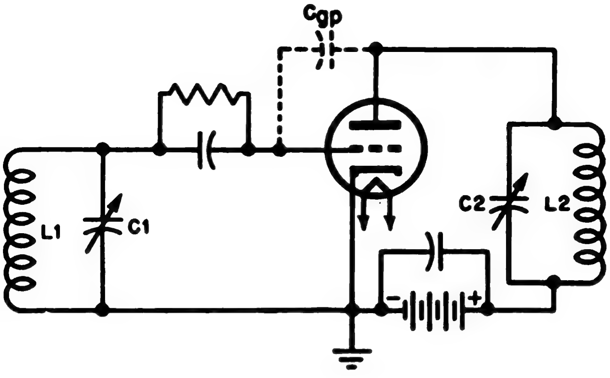

Figure 50. Tuned-plate tuned-grid oscillator.

Feedback takes place entirely through the grid-to-plate capacitance, C_{gp}, of the tube. It is not apparent immediately that the energy fed back from the plate-to-grid circuit is of the proper magnitude and phase to sustain oscillations in the grid tank. To understand the conditions required for oscillations to take place, an analysis of the grid in-put impedance of a triode and the effect of the plate load on this impedance is necessary. The following approximate analysis is not based wholly on oscillator operation, but holds for any triode amplifier. In addition to clarifying the conditions for oscillation, it will bring out the need for neutralization in a triode r-f amplifier.

b. Input Impedance of Triode.

(1) *Actual circuit.* In A of figure 51, $Z1$ is the impedance inserted in the grid circuit of the tube, and $Z2$ represents the plate-load impedance. In the TPTG oscillator, $Z1$ and $Z2$ represent the respective impedances of the grid and plate tank circuits. Z_{in} is the input impedance looking into the grid of the tube, neglecting $Z1$. In other words, Z_{in} is the impedance one would measure between grid and cathode of the tube, with plate load $Z2$ present, but with grid load $Z1$ not inserted. For reasons that will become apparent, Z_{in} can be represented by an equivalent input resistance, R_g, in parallel with an equivalent capacitance, C_g, both shunting grid load $Z1$. The interelectrode capacitances of the tube are C_{gk}, C_{gp}, and C_{pk}. The grid-to-cathode capacitance C_{gk}, is in parallel with the equivalent grid capacitance, C_g, and both added together evidently represent the total input capacitance shunting, $Z1$. The plate-to-cathode capacitance, C_{pk}, is in parallel with the plate-load impedance, $Z2$. In the TPTG oscillator, C_{pk} can be added to tank capacitor $C2$, both determining the resonant frequency of the plate tank circuit. The effect of grid-to-plate capacitance C_{gp} is to be determined.

(2) *Resistive case.* Assume that a grid voltage, e_g, is placed across the input of the tube, as in B of figure 51. If $Z2$ is purely resistive, the output voltage, e_p, is exactly opposite in phase to e_g and is amplified. It will be rememberered that the tube itself introduces this 180° phase shift between plate and grid voltage, and has an equivalent generator voltage of

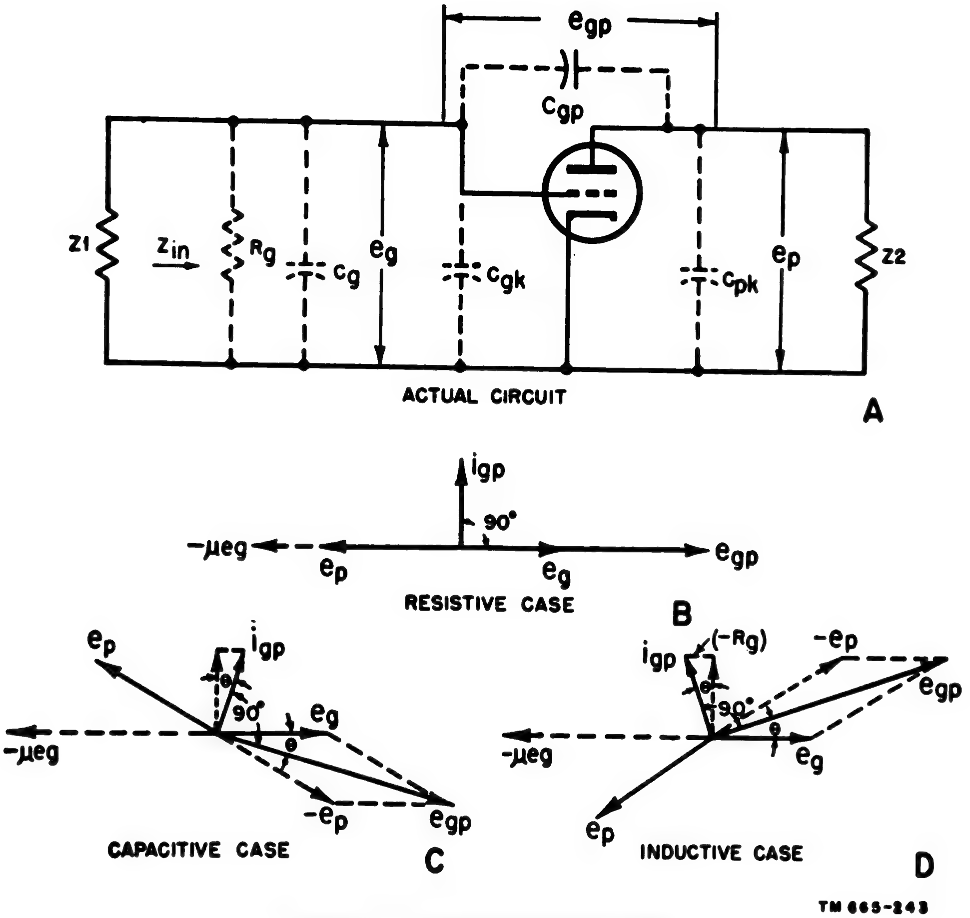

Figure 51. Input impedance of triode.

e_g. In the TPTG oscillator, $Z2$ is resistive, if the plate tank is exactly at resonance. The output voltage, e_p, is in phase with $-\mu e_g$, both being 180° out of phase with e_g. The voltage from grid to plate, e_{gp}, is the *vector difference* between e_g and e_p. This is obtained by reversing vector e_p and adding it to e_g; the result is shown as e_{gp}. Arithmetically, the magnitude of e_{gp} is simply the sum of e_g plus e_p for the resistive case. Current i_{gp} flowing in the grid-to-plate capacitance, C_{gp}, leads voltage e_{gp} across it by 90°, as shown. A quantitative picture can be obtained of the input impedance in this example. The current through C_{gp} is

$$i_{gp}=\frac{e_{gp}}{X_{cgp}}=\frac{e_g-(-e_p)}{X_{cgp}}$$

where X_{Cgp} is the capacitive reactance of the grid-to-plate capacitance, C_{gp}. The current, i_{gp}, through C_{gp} flows in the grid circuit where e_g is applied. By definition, the input impedance, Z_{in}, is e_g/i_{gp}. Consequently,

$$Z_{in}=\frac{e_g}{i_{gp}}=\frac{e_g}{e_g+e_p}\times X_{Cgp}=\frac{e_g}{e_g+e_p}\times\frac{1}{2\pi fC_{gp}}$$

It is evident that the input impedance is made up purely of capacitive reactance. To find the equivalent capacitance, C_g, we solve

$$Z_{in}=\frac{1}{2\pi fC_g}=\frac{e_g}{e_g+e_p}\times\frac{1}{2\pi fC_{gp}}$$

Canceling out $2\pi f$,

$$\frac{1}{C_g}=\frac{e_g}{e_g+e_p}\times\frac{1}{C_{gp}}$$

Hence, by inverting,

$$C_g=\frac{e_g+e_p}{e_g}\times C_{gp}=C_{gp}\times\left(1+\frac{e_p}{e_g}\right)$$

The total effective input capacitance, C_{in}, is simply C_g plus C_{gk} (two parallel capacitors), or

$$C_{in}=C_{gk}+C_{gp}\times\left(1+\frac{e_p}{e_g}\right)=C_{gk}+C_{gp}\times(1+A)$$

where

$A=e_p/e_g=$ amplification of the tube

Consequently, the total *dynamic input capacitance*, C_{in}, is considerably greater than C_{gk} alone.

Example: If the grid-to-plate capacitance, C_{gp}, is equal to 30 μμf, the grid-to-cathode capacitance, C_{gk}, equals 10 μμf, and a grid excitation of 5 volts produces an output voltage of 50 volts across a resistive load, what is the equivalent effective input capacitance?

$$C_{in}=C_{gk}+C_{gp}\left(1+\frac{e_p}{e_g}\right)=10+30\left(1+\frac{50}{5}\right)=10+330=340\ \mu\mu f$$

This value is 34 times the actual grid-to-cathode interelectrode capacitance. If the output voltage were reduced to zero (by short-circuiting the output), the input capacitance would be only 10 plus 30 equals 40 μμf, or less than one-eighth the value obtained with the output voltage present. The large voltage present across a high-impedance output tank circuit raises the effective input capacitance tremendously. If $Z1$ represents a tuned-grid tank circuit, as in the TPTG oscillator, this large input capacitance in parallel with the tank capacitor lowers the resonant frequency of the tank considerably.

(3) *Capacitive case.* Now assume that $Z2$ is a capacitive reactance plus a resistance. This is true if the plate tank circuit of the TPTG oscillator is at a frequency above resonance. (A parallel-resonant circuit is capacitive at a frequency above its resonant or natural frequency.) The voltage across a capacitance lags behind the applied voltage in an *R-C* circuit. Hence, the output voltage, e_p, lags behind the amplified grid voltage, $-\mu e_g$. Therefore, the phase shift between e_g and e_p is somewhat less than 180°, as shown in *C* of figure 51. The voltage, e_{gp}, across C_{gp} again is $-\mu e_g$, the vector difference e_g minus e_p, and is seen to have a lagging or negative angle, Θ, in respect to grid voltage e_g. The current, i_{gp}, through C_{gp} leads the voltage, e_{gp}, by 90°. This current may be resolved into a capacitive component at right angles to e_g and a resistive component in phase with e_g. The reactive component is only

slightly less than for the resistive case and again can be represented by a capacitance, C_g. The resistive component corresponds to an equivalent resistance, R_g, in parallel with the input impedance, $Z1$. This resistance acts as an additional load. As a result, the grid excitation voltage, e_g, is reduced. Thus, if the plate tank is mistuned by lowering its resonant frequency, power is lost in the grid circuit, and the excitation is reduced. This shows the importance of neutralizing the grid-to-plate capacitance, C_{gp}, even when no oscillations take place.

(4) *Inductive case.* The phase relations if output impedance $Z2$ is inductive in character are shown in D of figure 51. This corresponds to the case where the plate tank circuit of the TPTG oscillator is at a frequency below resonance—that is, where the resonant frequency of the tank has been raised by decreasing the capacitance of $C2$. The voltage across an inductor leads the applied voltage in an R-L circuit. The output voltage, e_p, therefore, leads the equivalent generator voltage, $-\mu e_g$, by some angle. Again, e_{gp} is the vector difference between e_p and e_g, and is obtained by reversing e_p, and adding $-e_p$ to e_g vectorially. As before, the current, i_{gp}, leads e_{gp} by 90°, and can be resolved into a reactive and resistive component. The capacitive reactance component is about as large as before, indicating that the equivalent capacitor, C_g, has not changed much in value. The resistive component, however, is now in a direction opposite to e_g, or is 180° out of phase with it. This indicates that energy is being transferred from the plate circuit to the grid circuit. As a result, the excitation or drive is increased. Since the current through a resistance is in phase with the voltage, the 180° out-of-phase component of i_{gp} is said to be caused by a *negative resistance.* A negative resistance represents a source of power. As shown in D, for a negative resistance to be present, the current, i_{gp}, through C_{gp} must lead e_g by more than 90°, and Θ is positive. This is possible only if output impedance $Z2$ is *inductive.*

c. Oscillator Action. As has been explained, a negative resistance represents a source of power, and its presence in the grid circuit tends to overcome the losses in the grid tank, $L1$-$C1$. For oscillations to take place, the losses must be overcome completely, so that the effective circuit resistance is zero.

d. Frequency Setting. In general, the frequency of oscillation is determined by the tuned L-C circuit that has the higher Q. In the TPTG oscillator, this is normally the grid tank circuit. It must be kept in mind, however, that the natural frequency of oscillation of the grid tank is lowered because of the presence of the large effective input capacitance in parallel with tank capacitance $C1$. To compensate for this effect, the grid tank circuit must be tuned to a frequency slightly higher than the desired frequency of operation by reducing $C1$. It has been shown that the plate tank circuit also must be tuned above the operating frequency to obtain the proper phase relations for oscillation.

e. Summary. The conditions which must be fulfilled to cause sustained oscillations in a tuned-plate tuned-grid oscillator are—

(1) Both the grid and plate tank circuit must be tuned to a frequency slightly higher than the operating frequency desired.

(2) Sufficient negative resistance must be present to supply all circuit losses.

38. Effect of Load on Oscillator

In the tuned-plate tuned-grid oscillator just discussed, the load in the plate circuit of the tube has a pronounced effect on the input impedance. The resistive component of the input impedance affects the Q of the grid tank, whereas the input capacitance affects its resonant frequency, since it is in parallel with the tuning capacitor. Changes in the output load, therefore, affect both the Q and the resonant frequency of the grid tank, and may shift the frequency of oscillations excessively. This is true not only for the TPTG oscillator, but true for all oscillators which utilize a tuned tank circuit. Whenever a load is coupled to a tank circuit, its Q and the resonant frequency are affected. Since frequency stability is of paramount importance in oscillator design because of the required close frequency tolerances, a consideration of the causes leading to frequency instability is discussed here.

a. Frequency Stability. The natural frequency of oscillation of a tank circuit is approximately equal to its resonant frequency. Since it is necessary, in modern transmitters, to maintain the frequency of the oscillator constant to a very high degree of precision, the *exact* frequency of oscillation and its dependence on external conditions must be known. For electron-tube oscillators, the exact frequency of oscillation is

$$f=\frac{1}{2\pi\sqrt{LC}}\times\sqrt{1+\frac{R}{R_p}}$$

where

R = total effective series resistance of the tank circuit,

R_p = plate resistance (a-c) of tube,

L = the inductance of the tank circuit,

C = total effective tank-circuit capacitance (including the effect of tube interelectrode capacitance).

Here, the effective series resistance, R, of the tank circuit is that caused by the resistance of the coil and conductors, as well as any additional resistance *reflected back* into the tank circuit because of coupling to a load. In general, if no load is coupled to the oscillator, the series resistance, R, is small (for a high-Q tank) compared to the plate resistance, R_p, and the second square-root term of the equation above can be neglected. The frequency of oscillations then is equal to the resonant frequency of the tank circuit. With power being drawn from the oscillator, however, the actual frequency of oscillation is somewhat higher than the resonant frequency, and all the factors in the equation must be taken into account. Frequency stability is highest when the oscillations tend to occur at a frequency that differs as little as possible from the resonant frequency ($1/2\pi\sqrt{LC}$). The conditions that affect the difference between the actual generated frequency and the resonant frequency of the tank then have proportionately less effect. The most important conditions that can cause frequency instability are the following: changes in tube characteristics, changes in temperature, vibration, and changes in load and/or coupling.

(1) *Tube characteristics.* The most important factor in this category is the dynamic or a-c plate resistance, R_p. A great many things can affect the plate resistance of an electron tube. Changes in the plate voltage, the average grid voltage, and the filament voltage all affect the plate resistance. The shift in frequency with plate-voltage variations (caused by changes in R_p) is called *dynamic instability.* This can be reduced by using a tuned circuit with a high effective Q and by loading it only lightly. The reason for this will become clear in the discussion of loading. Dynamic instability also can be improved by using a high value of grid-leak resistance. This increases the grid bias and raises the effective internal resistance of the tube as seen by the tank circuit. The internal resistance of the tube also is affected by interruption (keying) of the circuit and by changes in the spacing of the tube elements. The spacing of the tube elements may change because of mechanical vibration, heating, or aging of the tube. Since the interelectrode capacitances of the tube depend directly on the spacing of the elements, any variations directly affect the frequency of oscillation.

(2) *Temperature.* In addition to varying the spacing of the tube elements, changes in temperature affect the physical dimensions of the tank circuit coil and capacitor, thereby changing the frequency. In addition, the resistance of the coil and the load circuit may be altered because of temperature changes, again varying the frequency. In contrast to dynamic instability, temperature effects are relatively slow, and the frequency change caused by them is called *frequency drift.*

(3) *Vibration.* If the elements of the oscillator are not rigidly mounted, mechanical vibration may result in changing the relative positions of these parts, with consequent capacitance and frequency changes. A periodic mechanical vibration can frequency-modulate or *wobble* the carrier frequency, and is, therefore, usually audible at the receiver.

(4) *Effect of load.*

(*a*) If a load is connected directly across the resonant tank circuit, as in A of figure 52, it can be represented by a resistance in parallel with L and C of the tank. If a considerable amount of power is to be delivered to the load, the

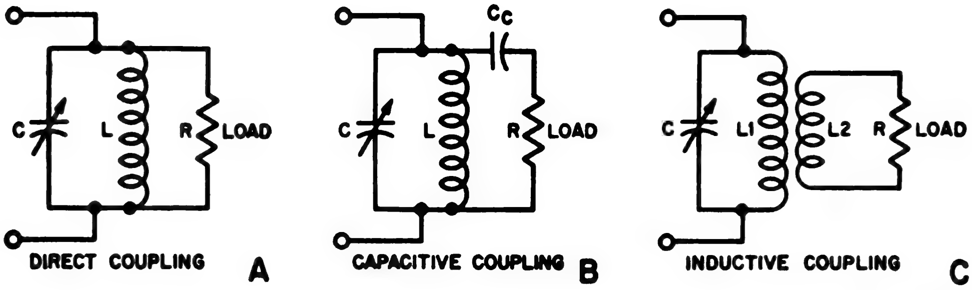

Figure 52. Coupling methods.

load resistance is small compared to the parallel impedance of the resonant tank circuit. For all practical purposes, then, the impedance of the combined circuit is equal to the load resistance (the lower of two parallel resistances). It has been explained previously that the parallel impedance of tank is equal to the product of Q and the reactance of either the coil or the capacitor. The lowering of the parallel impedance by connecting a load is equivalent to reducing the Q of the circuit. The *effective* Q of the tank is then,

$$Q=Z/X$$

where

Q=*effective* Q of tank circuit with load

Z=parallel *load* impedance (resistive) in ohms

X=reactance of either the coil or the capacitor

Example: A tank circuit has a series resistance of 5 ohms (associated with the coil), and inductive and capacitive reactances of 250 ohms, each. What is the Q of the circuit before and after a resistive load of 3,000 ohms is connected across it? Without load,

$$Q=\frac{X_L}{R}=\frac{250}{5}=50$$

With the 3,000-ohm load connected, the effective

$$Q=\frac{Z}{X}=\frac{3{,}000}{250}=12$$

Therefore, the Q is reduced to less than one-quarter of its unloaded value. As seen from the tank circuit, the load resistance is in parallel with the plate resistance of the tube, and, therefore, lowers its effective value. From the frequency equation, this increases the frequency above the resonant value. Consequently, a low effective Q contributes to frequency instability. Conversely, a high effective Q in the tank circuit will make changes in the effective plate resistance less noticeable and so improve frequency stability.

(*b*) Since $Q=Z/X$, the effective Q of the loaded tank circuit becomes higher when the reactances of the coil and capacitor are decreased at the resonant frequency. This can be done by decreasing L and increasing C in the tank circuit. In other words, the L-C ratio must be *lowered* to obtain a high effective Q for a given resonant frequency. A low L-C ratio will also reduce the *series* resistance, R, of the tank. The disadvantage of a low L-C ratio is low efficiency, because of the large circulating tank current and the low effective impedance of the tank.

(*c*) If the load is inductively coupled to the tank circuit, a resistance is coupled into the tank, acting in series with the coil resistance. This raises the effective series resistance, R, of the tank. This series resistance reflected from the load (secondary) circuit increases with the square of the mutual inductance between the coils—that is, with the amount of coupling. The reflected resistance also increases as the load resistance is made smaller. As the effective series resistance, R, is increased, the frequency of oscillation increases above the resonant value. However, tight coupling between the load and tank circuit and a low value of load resistance are the conditions required to obtain large power transfer to the load. It is clear, therefore, that large power output from the oscillator and good frequency stability are mutually incompatible. The tighter the load is coupled to achieve large power output, the lower is the frequency stability.

(*d*) Some means must be found to isolate the load from the tank circuit of the oscillator in order to obtain sufficient power output without consequent frequency instability. This can be done in various ways. The oscillator tank circuit might be only very lightly loaded, just sufficiently to excite the grid of a following amplifier. The load is coupled to the output of this amplifier, and has only a slight effect on the oscillator. If the amplifier is operated as a class C power amplifier, the arrangement is called a *master-oscillator power amplifier*. In this way, the oscillator operates with a light load and consequently under conditions favorable for frequency stability. Additional measures, such as crystal control and temperature control, generally are used to increase frequency stability still further. The master-oscillator amplifier can be combined into a single tetrode or pentode in an electron-coupled oscillator circuit.

b. Coupling Methods. Three coupling methods commonly are used to couple a load to an oscillator. These are direct or conductive coupling, shown in A of figure 52, capacitive or impedance coupling, in B, and inductive or transformer coupling, in C.

(1) The effect of direct coupling on the Q of the tank circuit has been discussed previously. The effective Q of the tank circuit can be increased somewhat at the expense of power output by tapping the load across a part of L. Direct coupling is the least favored of all coupling methods. It provides no d-c isolation between the tank circuit and the load.

(2) Capacitive coupling commonly is used in oscillator circuits. The coupling to the load increases as the coupling capacitance C_c, is made larger. The capacitance required for maximum energy transfer between the oscillator tank and load generally is quite small. But, again, the greater the coupling and consequent power output, the lower is the effective Q of the tank circuit, and the frequency stability consequently is reduced.

(3) When the load is coupled inductively to the oscillator, as in C, the two coils, $L1$ and $L2$, constitute the primary and secondary, respectively, of an air-core transformer, as explained in chapter 2. Also, as previously explained, the maximum power output (tight coupling) and frequency stability are incompatible in inductive coupling.

39. Electron-Coupled Oscillator

a. Principle. To minimize the effect of the load on the frequency of oscillation, electron-coupled oscillators frequently are used. These substitute a common electron stream to couple the load to the oscillator circuit, in place of inductive or capacitive output coupling. In figure 53, A shows a modified Hartley oscillator, and B is a modified Colpitts oscillator. In each, a single pentode fulfills the functions of both a triode oscillator and a buffer amplifier. The cathode, control grid, and screen grid (acting as the plate) form a triode oscillator of the conventional type. The load is coupled to the plate circuit of the pentode. The oscillator and plate circuit are coupled solely by the stream of electrons within the tube.

b. Analysis.

(1) Since the screen grid is at a positive voltage, electrons flow from cathode to screen grid, and oscillations are generated in the same manner as in the case of a conventional triode oscillator. The frequency is determined by the value of L and C in the grid circuit. Only a small number of electrons are intercepted by the screen grid. The remaining electrons, which represent most of the current, go on to the plate and through the load impedance. Since the screen-grid voltage varies with the oscillations, the intensity of the electron stream between screen grid and plate will be varied accordingly. In

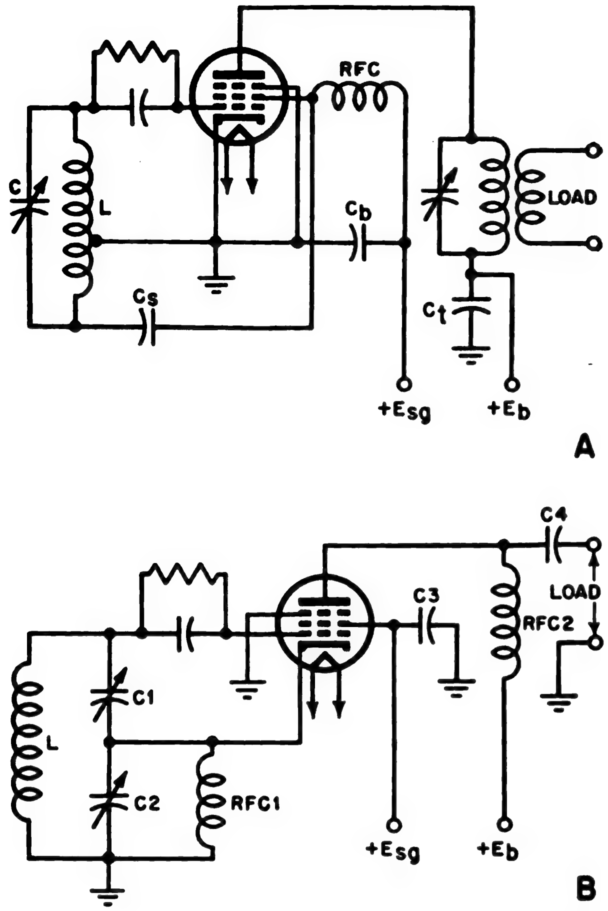

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Figure 53. Electron-coupled oscillators.

this way, the plate current is modulated at the oscillator frequency by the action of the screen grid and the control grid. Effectively, the screen grid and plate act as a triode whose control electrode voltage is varied at the oscillator frequency.

(2) Changes in the plate loading do not seriously affect the oscillation frequency. Coupling between the output (plate) and oscillator sections (screen grid) of the tube is minimized by the pentode construction, and by keeping the suppressor and screen grids at effective r-f ground potential. In tetrodes, neutralization of the screen grid-to-plate capacitance may be required. This is accomplished by connecting a capacitor of the proper value between plate and control grid. Pentodes do not require neutralization. Although the electron-coupled oscillator largely eliminates the effects of changes in plate loading by isolating the output circuit from the oscillator section, variations in temperature and tube voltages, mechanical vibrations, and spurious coupling affect the oscillator frequency in the same way as in conventional oscillator circuits. Adequate shielding against external coupling is especially important in electron-coupled oscillators. Mechanical vibrations in the tube directly modulate the electron stream, and therefore oscillator frequency, by changing the spacing between the tube electrodes. If tetrodes are used, variations in the plate-supply voltage can be compensated for by choosing the screen voltage properly from a tap on a common plate-supply voltage divider. This is possible, because plate-voltage and screen-voltage changes in a tetrode tend to change the frequency in opposite directions.

(3) In the modified Hartley oscillator, feedback is obtained from the screen grid through capacitor C_s. This makes possible operation of the cathode at ground potential. The screen grid is parallel fed through the radio-frequency choke, RFC, and capacitor C_b. Capacitor C_t grounds the lower end of the plate tank circuit for r-f. The use of the plate tank circuit makes possible frequency doubling or tripling by tuning the output to the second or third harmonic of the grid-circuit fundamental frequency.

(4) The ground point in the modified Colpitts circuit has been shifted from the cathode to the screen grid. The ratio of $C1$ to $C2$ determines the amount of feedback. RFC1 is required to provide a d-c path to the cathode without grounding it for r-f. Here an untuned output circuit with capacitive coupling is shown, although a tuned-plate tank could be used. The combination of RFC2 and capacitor $C4$ also serves to minimize the load reaction on oscillator frequency, but the power output obtainable with this arrangement is much lower than for a tuned-plate tank circuit. In either case, the power output of an electron-coupled

oscillator is less than that obtainable with the same tube in a conventional oscillator circuit.

c. Advantages. Although electron-coupled oscillators combine simplicity with excellent frequency stability, they produce a poor waveform and their output is correspondingly rich in harmonics. This may be an advantage for frequency doubling or tripling, as explained above. In contrast to the more stable crystal oscillators, electron-coupled oscillators permit continuous frequency variation.

40. Quartz Crystals

The most satisfactory method of stabilizing the frequency of radio-frequency oscillators is by the use of quartz crystals. These crystal-controlled oscillators are used in the majority of commercial and military radio transmitters.

a. Piezoelectric effect.

(1) The control of frequency by means of crystals is based upon the piezoelectric effect. When certain crystals are compressed or stretched in specific directions, electric charges appear on the surface of the crystal. Conversely, when such crystals are placed between two metallic surfaces across which a difference of potential exists, the crystals expand or contract.

(2) Consequently, if a slice of a crystal is compressed along the width, or stretched along its length, so that it bulges inward as in A of figure 54, opposite electrical charges appear across its faces, and a difference of potential is generated. If the crystal is squeezed or compressed lengthwise, so that it bulges outward, as in B, the charges across its faces reverse. If alternately stretched and squeezed, a crystal slice becomes a source of alternating voltage. Conversely, if an alternating voltage is applied across the faces of a crystal wafer, it vibrates mechanically. The amplitude of these vibrations is very vigorous when the frequency of the a-c voltage is equal to the natural mechnical frequency of vibration of the crystal (resonance occurs). If all mechanical losses are overcome, the vibrations at this natural frequency will sustain themselves and generate electrical oscillations of constant frequency. Accordingly, a crystal can be substituted for the tuned tank circuit in an electron-tube oscillator.

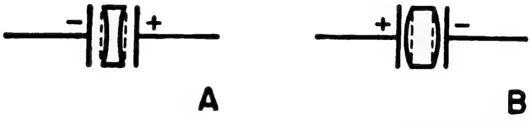

Figure 54. Crystal expansion and contraction.

b. Types of Crystals. Practically all crystals exhibit the piezoelectric effect, but only a few are suitable as the equivalent of tuned circuits for frequency-control purposes. Among these are quartz, Rochelle salt (sodium potassium tartrate), and tourmaline, of which Rochelle salt is the most active piezoelectric substance; that is, it generates the greatest amount of voltage for a given mechanical strain. These substances are physically and electrically unstable, however, and therefore, not suitable for frequency control. Rochelle salt has found applications in microphones, crystal speakers, and phonograph pickups. Tourmaline is almost as good as quartz over a considerable frequency range, and is somewhat better than quartz in the range from 3 to 30 mc, but it has the disadvantage of being a semiprecious stone. Its consequent high cost excludes it from general use. Quartz, although much less active than Rochelle salt, is used universally for frequency control of oscillators, because it is cheap, mechanically rugged, and expands very little with heat. Quartz is among the most permanent materials known, being chemically inert and very hard physically. Of all materials, it has been found to be the most satisfactory.

c. Crystal cuts.

(1) *Axes.* Natural quartz crystals have the general form of a hexagonal prism with six sides, sometimes topped on the ends by a hexagonal pyramid. They are rarely found as symmetrical as that shown in A of figure 55. Assuming, however, a symmetrical crystal, the cross section is hexagonal, as in B and C. The axis joining the points at each end, or apex, of the crystal is known as the optical or Z-axis. Stresses along this axis produce no piezoelectric effect. The three axes, X, X′ and X″, passing through the corners of

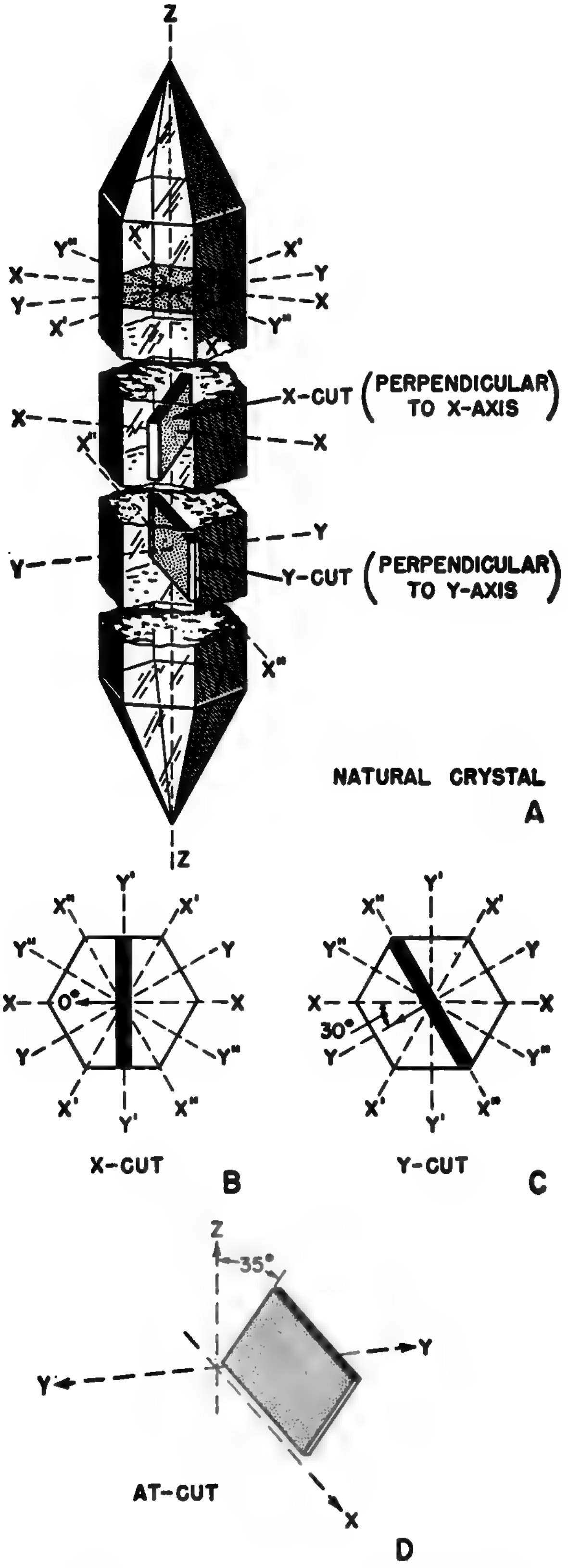

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Figure 55. Quartz crystal axes and cuts.

the hexagonal cross section at right angles to the Z-axis are known as the *electrical axes*, because they are the directions of greatest piezoelectric activity. The three axes, Y, Y′, and Y″, which are perpendicular to the faces of the crystal as well as to the Z-axis, are called *mechanical axes*. A mechanical stress in the direction of any Y-axis produces an electrostatic stress, or charge, in the direction of that X-axis which is perpendicular to the Y-axis involved. The polarity of the charge depends on whether the mechanical strain is a compression or a tension. Conversely, an electrostatic stress, or voltage, applied in the direction of any electrical axis, produces a mechanical strain, either an expansion or a contraction, along that mechanical axis which is at right angles to the electrical axis. For example, if a crystal is compressed along the Y′-axis, a voltage will appear on the faces of the crystal along the X-axis. If a voltage is applied along the X″-axis of a crystal, it will expand or contract in the direction of the Y-axis. This interconnection between mechanical and electrical properties is exhibited by practically all sections cut from a piezoelectric crystal.

(2) *Common crystal cuts.* Crystal wafers can be cut from the natural mother crystal in a variety of directions along the axes. They are known as *cuts*, and are identified by such designations as X, Y, AT, BT, V, R, etc. Each has certain advantages, but, in general, one or more of the following properties are desired: ease of oscillation at intended frequency, a single frequency of oscillation, and minimum frequency changes resulting from temperature changes. The *X-cut* is sliced along a Y-axis and has its main parallel faces perpendicular to an X-axis, as in B of figure 55. Although the diagram shows the section taken from the center of the crystal, the plate can be sliced from any part of the crystal, provided the orientation in respect to the axes is maintained. C illustrates the Y-cut, the long parallel faces of which are perpendicular to a Y-

axis. This type is known also as a 30° cut, because the Y-axis passing through its center is at an angle of 30° in respect to the nearest X-axis. X- and Y-cuts have unfavorable temperature characteristics, as will be explained later. Better characteristics can be obtained by cutting plates at different angles of rotation about the X-axis. The Y-cut serves as zero-degree reference, since it is lined up with both X- and Z-axes; that is, it lies in a plane formed by the X- and Z-axes. Now, assume that the crystal wafer is rotated about the X-axis in a clockwise direction, so that it forms an angle of 35° with the Z-axis, as in D. The resulting slice is called the *AT-cut*. If the crystal plane is rotated 49° in a counterclockwise direction about the X-axis, the resulting slice is called the *BT-cut*. Many other cuts exist, but they will not be discussed here.

41. Frequency of Crystal Oscillation

a. Modes. Most crystals have at least two principal ways or *modes* in which they can vibrate. They can bulge in and out perpendicularly to their long parallel faces (fig. 54) or they can stretch and contract along the width of these faces so that their short parallel faces bulge in and out.

(1) In the first case, called *thickness vibration*, pressure waves travel through the crystal from one long face to the opposite face and are reflected back again. At a particular thickness of the crystal, the reflected waves are in phase with the direct waves, and they reinforce each other. As a result, standing waves are created between the two long faces of the crystal, and the crystal is said to be in *resonance*. The fundamental natural frequency of oscillation occurs at that particular thickness, where at least one complete wavelength can exist between the two long faces. However, for the same thickness, two or more shorter complete wavelengths can also exist between the two faces. The crystal can vibrate at the second, third, or higher multiple (harmonic) of its fundamental frequency. For a given thickness, the fundamental frequency of the first principal mode is fixed.

(2) The second principal mode of vibration (the short parallel faces bulging in and out) is determined by the width of the plate, as measured along the long parallel faces. It is known as *width vibration*. Again, standing waves occur at the natural frequency of oscillation, and harmonics of this fundamental frequency are possible. Besides these principal modes and their harmonics, additional modes of vibration produced by various bending and twisting tensions are possible. The thinner the crystal, the more numerous are these resonances. The increasing complexity of operation as the crystal plate becomes thinner sets a practical limit to the highest frequency (smallest thickness), that can be generated.

b. Frequency Thickness Ratio.

(1) The thinner the crystal vibrating in its first mode, the higher is the frequency of oscillation. The fundamental frequency of thickness vibration is

$$f=\frac{K}{t}$$

where

K=constant, depending on the type of cut (see table below)

t=thickness in thousandths of an inch (mils)

f=frequency in megacycles (mc)

To compute the frequency of the second principal mode, width vibration, substitute the width, w, of the crystal for thickness, t, in the preceding formula. The formula for *width vibration* is, then,

$$f=\frac{K}{w}$$

where

K and f are the same as above

w=width of crystal in thousandths of an inch (mils).

Since the width of a given crystal is considerably greater than its thickness, width vibration produces a substantially lower fundamental frequency than does thickness vibration. Width vibration, therefore, is used for low-frequency crystals.

The frequency constant, K, for four commonly used cuts is shown below:

Type cut	Frequency constant, K
X	112.6
Y	77.2
AT	66.2
BT	100.78

Example: What is the thickness of an X-cut crystal for an operating frequency of 1.1 mc? If the same crystal has a width of 1.25 inches, what is the fundamental frequency for width vibration?

$$f=\frac{K}{t}$$

$$t=\frac{112.6}{1.1}=102.4 \text{ mils or } .124 \text{ inch}$$

For width vibration

$$f=\frac{K}{w}=\frac{112.6}{w}$$

The width of the crystal is 1.25 inches or 1,250 mils. Hence,

$$f=\frac{112.6}{1{,}250}=.09 \text{ mc or } 90 \text{ kc}$$

The fundamental frequency of the width vibration, therefore, is less than one-twelfth of the thickness vibration. Special dual-frequency crystals are available which oscillate both in the thickness and in the width mode.

(2) Quartz crystals are produced for frequencies from about 50 kc to as high as 50 mc, a range of 1,000 to 1. No single type of cut can cover this tremendous frequency range. Referring to the preceding table for K, it is apparent that for a given frequency the X-cut is the thickest, the BT- and Y-cuts are of intermediate thickness, and the AT-cut is the thinnest. For low frequencies, X- and Y-cuts, using width vibration, are used frequently. The characteristics of these cuts are not favorable for high frequencies, since for thin plates they have several frequencies of oscillation quite close together which can be simultaneously excited. This is particularly true for thin Y-cuts, whose thickness frequency depends somewhat on their width, because of mechanical coupling between the two modes. For frequencies from about 300 kc to about 5 mc, the AT-cut is preferred, since it has few resonant frequencies, and its fundamental frequency remains practically constant with changes in temperature. BT-cuts generally are used for frequencies above 5 mc, since they are thicker than AT-cuts for the same frequency and, therefore, less subject to fracture in operation. Many crystals used for very high frequencies are of the harmonic type; that is, their thickness corresponds to a frequency of one-third or one-fifth of the normal operating frequency. The other dimensions of these crystals are so proportioned that mechanical vibration is at three or five times the fundamental frequency.

c. Temperature Coefficient.

(1) *Frequency drift.*

(*a*) The resonant frequency of quartz crystals is practically unaffected by changes in the load. Like most other materials, however, quartz expands slightly with an increase in temperature. This affects the resonant frequency of the crystal. The *temperature coefficient* of the crystal refers to the increase or decrease in the resonant frequency, usually expressed in ppm (parts per million) or cycles per megacycle for an increase in temperature of 1° C. The temperature coefficient varies widely with different crystal cuts, and this is one of the chief reasons for the preference of the AT- and BT-cuts. These cuts have practically zero temperature coefficient in normal use. The temperature coefficient also depends on the surrounding temperature at which it is measured, and whether thickness or width vibration is used.

(*b*) Heating of the crystal can be caused by external conditions such as the high temperature of transmitter tubes and other components. Heating also can be caused by excessive r-f currents flowing through the crystal. The slow shift of the resonant frequency resulting from crystal heating is called *frequency drift.* This is avoided by use of crystals with nearly zero temperature coefficient, and also by maintaining the crystal at a constant temperature.

(*c*) The older X- and Y-cuts have poor temperature coefficients. The temperature coefficient of the X-cut is about −20 cycles per megacycle per degree for both thickness and width vibration. The negative coefficient indicates that the frequency *decreases* as the temperature *increases.* The Y-cut has a negative temperature coefficient of approximately −20 cycles per megacycle per degree for width vibration, and for thickness vibration the coefficient varies between −20 to +100 cycles per megacycle per degree. The exact value depends on operating temperature and the ratio of width to thickness. The approximate temperature coefficients for the AT- and BT-cuts at various operating temperatures are listed below:

AT-cut: +10 cycles per megacycle per degree at 0° C.
0 cycle per megacycle per degree at 45° C.
+20 cycles per megacycle per degree at 85° C.
BT-cut: −10 cycles per megacycle per degree at 0° C.
0 cycle per megacycle per degree at 30° C.
−20 cycles per megacycle per degree at 70° C.

Since the temperature coefficients of the AT- and BT-cuts vary somewhat with the operating temperature, a constant frequency can be obtained only by maintaining the surrounding temperature constant.

Example: Calculate the frequency drift of an X-cut crystal operating at 2.5 mc if the temperature increases from an initial value of 0° C to 25° C. What is the drift for an AT-cut crystal operating under the same conditions? For the X-cut, the drift is −20 cycles times 2.5 mc times 25° = −1,250 cycles. Hence, the new resonant frequency is 2,500,000 minus 1,250 = 2,498,750 cycles, or 2.49875 mc. For the AT-cut, the drift is +10 cycles times 2.5 mc times 25° = +625 cycles. Hence, the new resonant frequency for the AT-cut crystal is 2,500,000 plus 625 = 2,500,625 cycles or 2.500625 mc. Actually, the frequency drift for the AT-cut crystal is even less than this value, since the temperature coefficient, as shown above, becomes lower as the crystal heats up. Since the permissible frequency tolerance may be as low as about 20 cycles, the need for maintaining the crystal at a constant temperature becomes apparent.

(2) *Temperature maintenance.* To maintain the extremely close frequency tolerances required, the general practice is to construct the entire oscillator assembly in such a manner as to provide for nearly constant temperatures. This helps to avoid frequency drift resulting from contraction and expansion of circuit elements. The tube voltages are kept as constant as possible by suitable voltage-regulator circuits. In addition, the quartz crystal is operated in a constant-temperature oven. This oven is heated electrically and is held at constant temperature by special thermostats. The thermostats determine accurately any temperature variation and cause more or less current to flow through a heater element. The entire assembly usually is constructed of an aluminum shell inclosed by thick layers of insulating material to insulate the assembly. For extreme stability, the entire compartment can be placed inside still another temperature-controled box. In this way, frequency stabilities as high as 1 part in 10,000,000 or better can be attained.

42. Crystal Mounting

Crystals become practical circuit elements when they are associated with a crystal holder. In a holder (A of fig. 56), the crystal is placed between two metallic electrodes and forms a capaci-

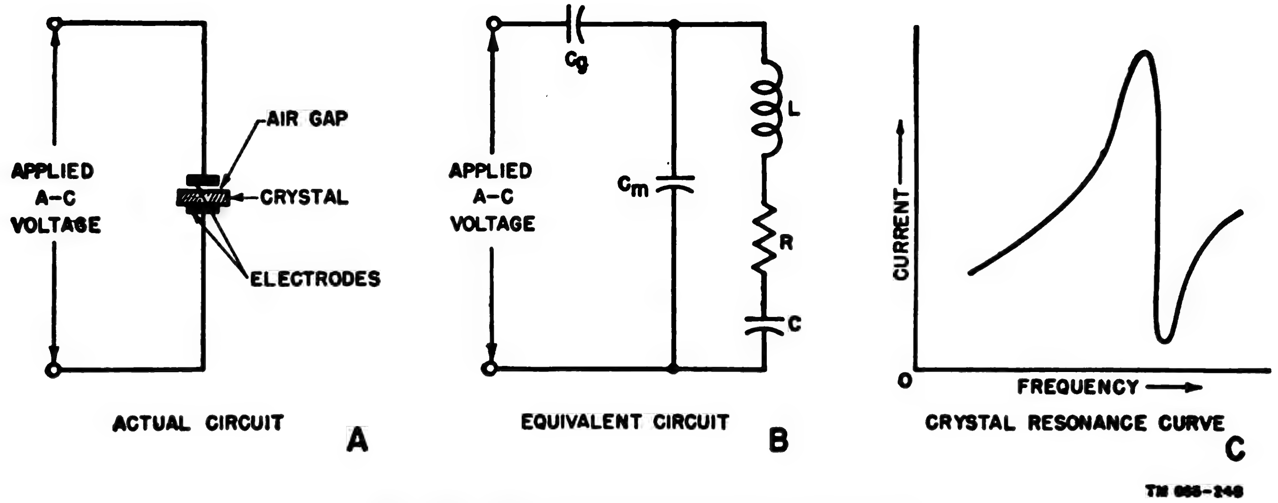

Figure 56. Equivalent circuit of crystal and mounting.

tor, the crystal itself being the dielectric. The crystal holder is arranged to add as little damping of the vibrations as possible, and yet it should hold the crystal rigidly in position. This is accomplished in various ways. In some holders, the crystal plate is clamped firmly between the metal electrodes; other holders permit an air gap between the crystal plate and one or both electrodes. The size of the air gap, the pressure on the crystal, and the size of the contact plates affect the operating frequency to some degree. The use of a holder with an adjustable air gap permits slight adjustments of frequency to be made. For the control of appreciable amounts of power, however, a holder which clamps the plate firmly usually is preferred. Figure 57 shows various types of crystal holders. A blank is shown in *E* of the illustration and is designed to fit into the holder, as shown in *C*.

43. Equivalent Circuit

a. At its resonant frequency, a crystal behaves like a tuned circuit so far as the electrical circuits associated with it are concerned. The crystal and its holder can be replaced, therefore, by an equivalent electrical circuit (*B* of fig. 56). Here, C_m represents the capacitance of the mounting, with the crystal in place between the elctrodes but not vibrating. C_g is the effective series capacitance introduced by the air gap when the contact plates do not touch the crystal. The series combination, L, R, and C, represents the electrical equivalent of the vibrational characteristics of the quartz plate. The inductance, L, is the electrical equivalent of the crystal mass effective in the vibration. C is the electrical equivalent of the mechanical compliance (elasticity). R represents the electrical equivalent of the mechanical friction during vibration. The capacitance of the holder, C_m is about 100 times as great as the vibrational capacitance, C, of the crystal itself.

b. The frequency at which L and C are in series resonance is the frequency of mechanical crystal resonance. Because of the presence of C_m, the circuit also has a parallel-resonant frequency slightly above series resonance. Parallel resonance occurs when the series branch has an inductive reactance equal to the capacitive reactance of C_m. (A series L-C circuit is inductive above its resonant frequency.) Since C_m has a comparatively low reactance (high C), only a small inductive reactance is required in the L-C-R branch to produce parallel resonance with C_m. Therefore, the series- and parallel-resonant frequencies are very close together. The presence of both resonant frequencies is clearly revealed by the crystal resonance curve, in *C* of figure 56. This curve is extremely sharp, and *Q*'s of over several thousand are attainable easily. It is found in practice that the L-C ratio of the equivalent circuit is extremely large compared with that of a conventional tank circuit.

44. Crystal Oscillator Circuit

a. The circuit of a commonly used crystal oscillator is seen (fig. 58) to be the equivalent of the tuned-plate tuned-grid oscillator, but with the crystal replacing the grid tank circuit. Feed-

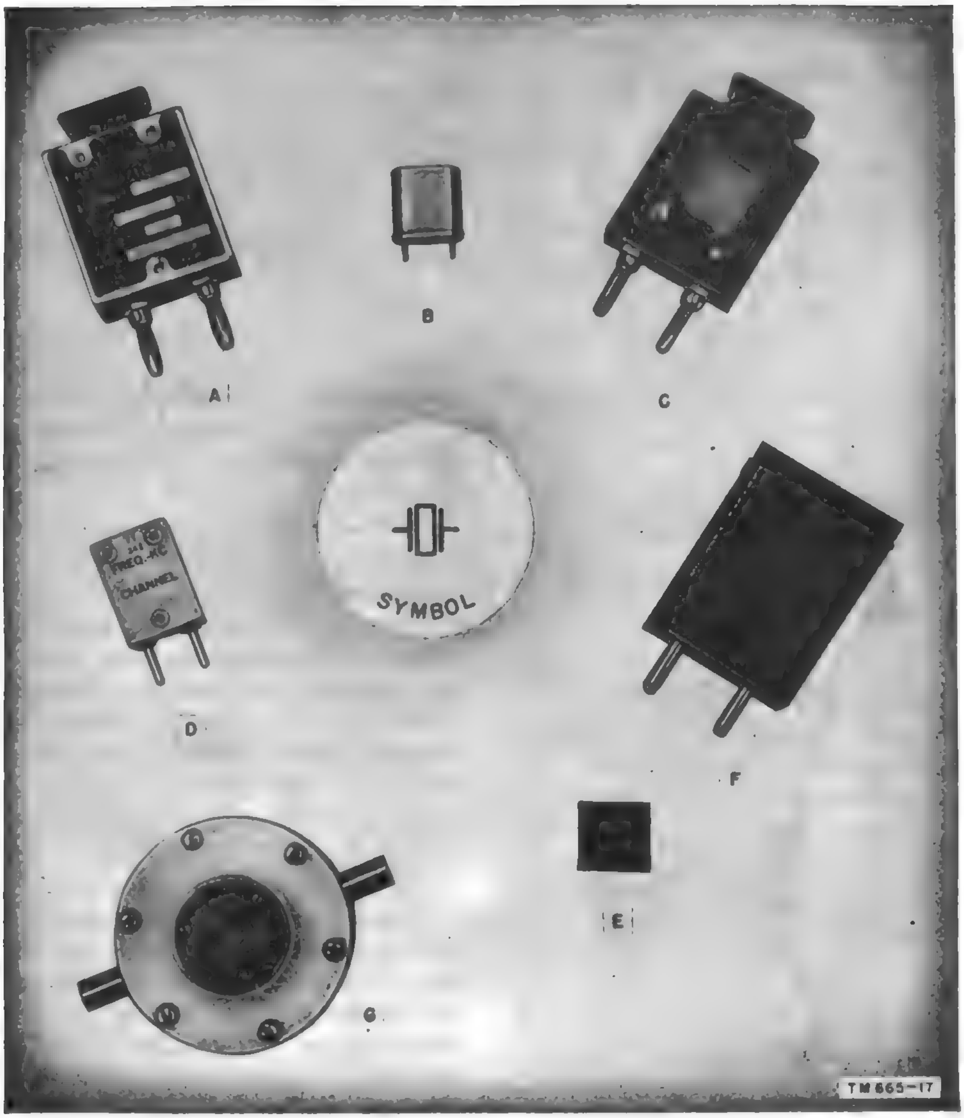

Figure 57. Crystal holders.

back is obtained through the grid-to-plate capacitance, C_{gp}. The choke, RFC, keeps r-f out of the grid-leak resistor, which provides the bias. The crystal functions in the same manner as the grid tank circuit of the TPTG oscillator. It stores energy in mechanical form during one-half of the excitation voltage cycle, and releases it in electrical form during the second half of the cycle. The rate of storage and release of energy depends on the natural resonant frequency of the crystal and so determines the frequency of oscillation generated by the circuit. The losses in the crystal are overcome by the energy fed back through C_{gp}. The coupling between the tube and the crystal is determined primarily by the ratio C/C_m (B of fig. 56), which was seen to be very small. This small coupling, which is much less than in the TPTG oscillator, further improves frequency stability. As in the TPTG oscillator, the plate-tank circuit must be inductive, so that a negative resistance appears in the grid input circuit in parallel with the crystal to overcome the losses.

b. The resonance curve of the crystal shown is obtained by tuning the plate circuit from a frequency below crystal resonance to one above crystal resonance. As the frequency is increased, series resonance of the crystal (mechanical resonance) is reached first, as indicated by the high crystal current peak in the resonance curve. The impedance is a minimum, and hence the current

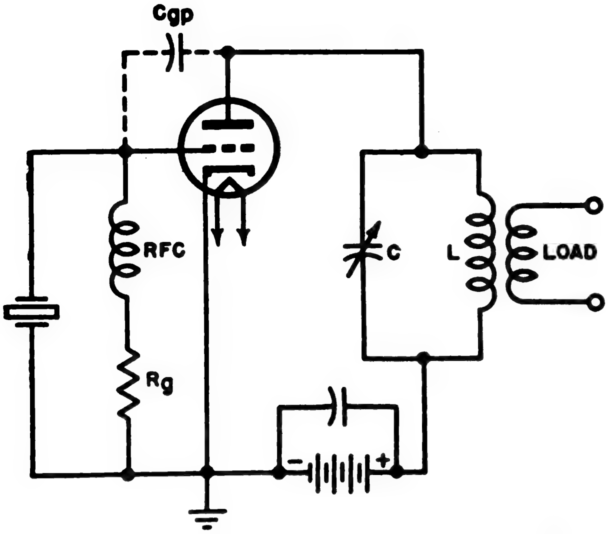

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Figure 58. Typical crystal oscillator circuit

is a maximum for series resonance. In spite of the large current, oscillations cannot start because of improper phase relations. When the frequency of the plate tank is increased slightly above this value, parallel resonance of the crystal is reached; that is, the inductive reactance of the crystal proper equals the capacitive reactance of the crystal holder capacitance. This is indicated by the sharp drop of the crystal current in the resonance curve, and consequent high crystal impedance. Oscillations still cannot take place, however, since the plate tank is resistive at resonance. Another slight increase in frequency makes the plate circuit inductive, as required, and oscillations commence. Since this frequency is above crystal resonance, the equivalent crystal circuit is also slightly inductive. This inductive reactance is canceled out by the effective grid input capacitance, so that the entire grid circuit (crystal plus tube input capacitance) is in parallel resonance. Maximum power output of the oscillator occurs at this frequency. If the frequency of the plate tank is increased still further, the plate tank impedance drops and less energy is fed back. Also, the increasing effective capacitance across the crystal shunts the crystal and robs it of excitation. Under these conditions, oscillation stops. The presence of oscillations can be detected by a sharp drop in plate current as the frequency of the plate tank is raised.

c. Since the crystal can oscillate only at its resonant frequency, the frequency of oscillation remains constant at that value over a wide range of adjustment of tuning capacitor *C*. The power output changes substantially, however, when *C* is varied. Nevertheless, because of the shunting effect of the effective input capacitance in parallel with the crystal, the frequency of oscillations can depart slightly from the crystal resonance frequency for appreciable detuning of the plate tank without stopping the oscillations. For example, an increase of 2 percent in the tuning capacitance of the tank can reduce the frequency of oscillations by about 20 cycles per megacycle. Changes in plate voltage, filament voltage, and replacement of tubes also have very slight effects on the frequency of oscillation.

d. The outstanding characteristic of the crystal is the extreme sharpness of its resonance curve because of a very high effective *Q*. Because of this characteristic, the crystal can oscillate only over a very narrow frequency range, and, consequently, the frequency stability of a crystal oscillator is extremely high. This is taken advantage of in military communication equipment where close frequency tolerances are desired. Crystal oscillators are used not only in fixing the frequency of transmitters, but also as frequency standards for measurement purposes. If a low-frequency crystal is used in a circuit whose output is not tuned, a large number of harmonics is created. Therefore, a great number of calibration frequencies can be obtained with a single quartz crystal. A crystal-controlled oscillator is a fixed-frequency oscillator. A disadvantage is that a different crystal must be used for each desired frequency (or multiples of that frequency). In many applications, it is required to change the frequency of the transmitter rapidly and continuously. For these applications the ordinary variable-frequency oscillator is preferred, since it may be operated at any frequency within a band at the turn of a dial. Another limitation of the crystal oscillator is its relatively low power output. The power obtainable from a crystal oscillator is limited at low frequencies by the strains which the vibrations set up in the crystal structure. If the vibrations are too intense, they will crack the crystal. At high frequencies, the available power is limited by heating of the crystal. The heating is produced by the large r-f crystal current necessary to obtain the excitation for substantial power output. Crystal heating short of the danger point results in frequency drift, thus lowering frequency stability.

Excessive r-f current can fracture the crystal. By pushing the crystal to the limit, 50 to 100 watts can be obtained from a crystal oscillator. It usually is preferred, however, to operate the crystal with a light load, and obtain the required power through amplification in succeeding stages of the transmitter. In general, the crystal oscillator is considered as a frequency-generating device, with power output of secondary importance.

45. Care of Crystals

a. Minute particles of dust and grease that collect on the crystal will interfere with its operation. The crystal must be free from dirt, finger marks, oil spots, and so forth, or it will operate erratically. High-frequency crystals, especially, are susceptible to small impurities and consequent erratic operation. A simple cleaning usually will restore the crystal to its original condition.

b. Care must be taken in cleaning not to chip or crack the crystal. A good cleaning agent is carbon tetrachloride or other dirt and grease solvents. Soap and water are effective, but require great care, as vigorous scrubbing is necessary. After washing, the crystal should be dried with a clean lint-free cloth. At this point, the fingers must be kept off the major faces of the crystal to prevent oily finger marks. The crystal can be handled by its edges or with tweezers. The same procedure should be followed with the surfaces of all electrodes. When replacing the crystal in its holder, it must be located properly. If the crystal electrodes are removable from the holder, the crystal must be placed between the electrodes in such a manner that the finely finished faces of the electrodes are in contact with the crystal.

46. Pierce Crystal Oscillator

a. The circuit of the Pierce oscillator (fig. 59) is very similar to that of the Colpitts oscillator, with the crystal replacing the tank coil, L (fig. 48), and the tube grid-to-cathode capacitance, C_{gk}, and plate-to-cathode capacitance, C_{pk}, replacing capacitors $C1$ and $C2$. Since the crystal itself represents a tuned circuit, the tube capacitances, C_{gk} and C_{pk}, act only as a capacitive a-c voltage divider, and do not influence the frequency of oscillation. Their ratio determines the amount of feedback from plate to grid and, therefore, the amount of crystal excitation. Since excitation is not otherwise adjustable, except by a change in the plate voltage, the variable capacitor, C, between the grid and the cathode sometimes is required to adjust the amplitude of oscillation. The tube is parallel-fed through choke RFC and capacitor C_b. A triode is shown in the figure, but a tetrode or pentode can be used equally well. The output is coupled capacitively. The crystal is connected between the plate and grid, since blocking capacitor C_b has only a small reactance.

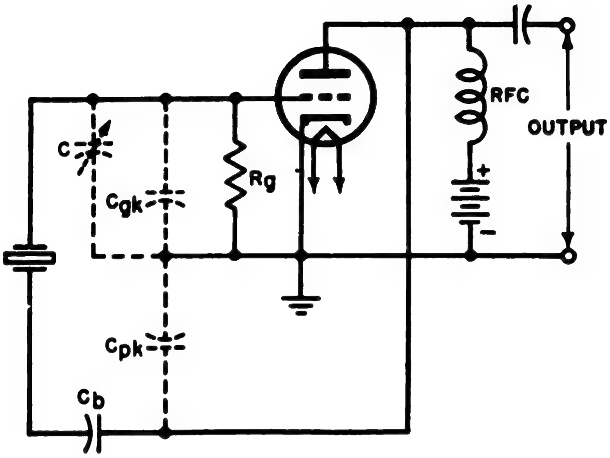


Figure 59. Pierce oscillator.

b. Since there are no actual tuned circuits in the Pierce oscillator, the frequency of oscillations generated by the tube is determined solely by the crystal. The oscillator requires no tuning adjustments, and operates without change in the values of components over a wide range of crystal frequencies. Less power is obtainable from the Pierce circuit than from the preceding TPTG crystal oscillator, because the crystal is directly in the power-delivering circuit. This limits the r-f output voltage that can be developed without danger to the crystal. The Pierce circuit, therefore, finds application in low-powered oscillators at high frequencies, such as test and calibrating oscillators.

47. Tri-Tet Oscillator

a. The tri-tet oscillator (fig. 60) combines the principles of the triode crystal oscillator with those of the electron-coupled oscillator and, consequently, attains some of the advantages of both. Because of electron-coupling, the output (plate) circuit reacts very little on the oscillator portion. This is of importance for reliable keying in transmitters. In addition, the crystal is lightly loaded in the tri-tet circuit, which contributes to high frequency stability.

b. The oscillator portion is the equivalent of the simple triode crystal oscillator, TPTG, shown in figure 58. The screen of the tetrode serves as the *plate* of the triode oscillator, and the ground point is shifted from the cathode to the screen grid. Power is taken from the separate output tank circuit, *L*2-*C*2, through capacitor *C*4. Feedback takes place primarily through the control-grid to screen-grid capacitance, C_g, which corresponds to the gride-to-plate capacitance, C_{gp}, of the simple TPTG triode oscillator. The plate circuit also contributes to the feedback, since the plate output circuit returns to the cathode through the *L*1-*C*1 tank circuit. To prevent excessive feedback and crystal heating, therefore, tank *L*1-*C*1 should be tuned well to the high-frequency side of the crystal frequency, so that just sufficient energy is fed back to make the circuit oscillate. In this way, the crystal is loaded only lightly, and yet it provides oscillations of sufficient amplitude to modulate the electron stream between screen grid and plate. Amplification takes place in the screen grid-plate portion of the tube and through the plate tank circuit, *L*2-*C*2.

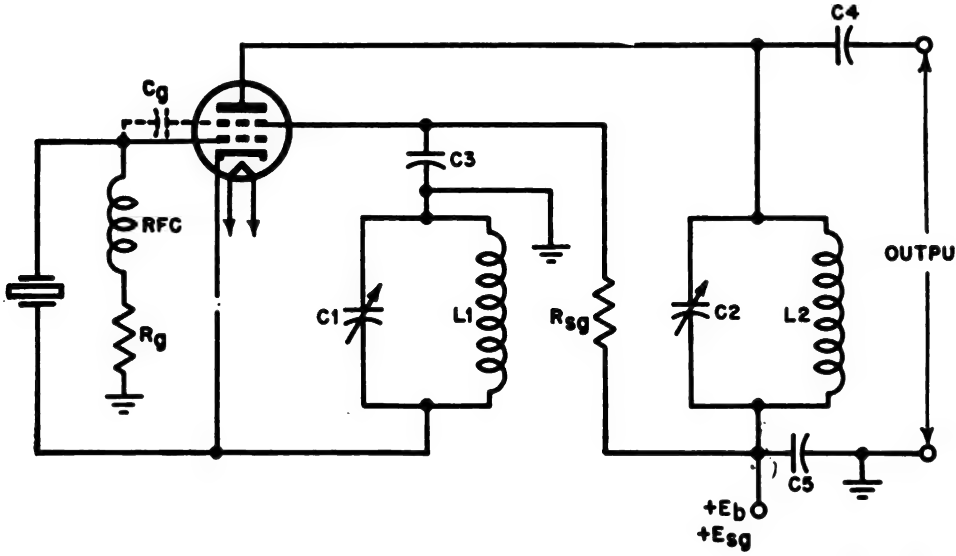


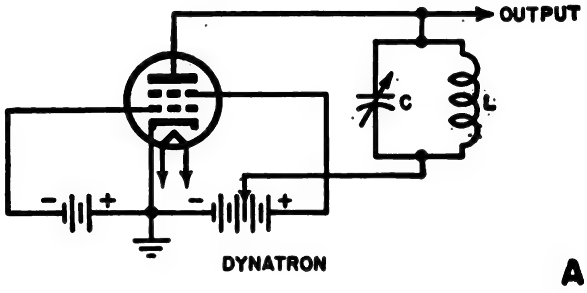
Figure 60. Tri-tet oscillator.

c. With well-screened tetrodes or pentodes, the circuit oscillates regardless of the output tuning. As with the electron-coupled oscillator, frequency doubling or tripling can be obtained by tuning *L*2-*C*2 to the desired multiple of the crystal frequency.

48. Negative-Resistance Oscillators

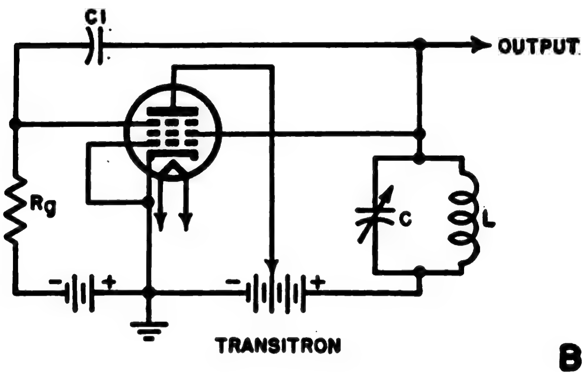
The desire for greater flexibility and the necessity for generating oscillations at ultrahigh frequencies for radar and other applications have led to unconventional ways of operating standard tubes and to the development of entirely new types radically differing from ordinary vacuum tubes. It has been shown in the analysis of the TPTG oscillator that a negative resistance can be used to counteract the positive resistance of a parallel-resonant tank circuit. It was shown further that oscillations begin when the value of the negative resistance is less than the positive resistance of the tank circuit. When the total effective circuit resistance is zero, sustained oscillations are generated. In a positive resistance, the current increases as the voltage across it is increased. In a negative resistance, the opposite takes place. The current *decreases* as the voltage is increased. As a result, such a resistance does not consume but generates power.

a. Dynatron. A tetrode exhibits negative resistance when the plate voltage is less than the potential on the screen grid. This is indicated by the reversed plate-characteristic slope and is caused by secondary emission from the plate. If, on the average, more secondary electrons flow to the positive screen grid than the number of primary electrons received by the plate, then the net plate current decreases with an increasing plate voltage. This produces the effect of negative resistance. The dynatron oscillator (A of fig. 61) is essentially a tetrode operated with the plate less positive than the screen grid, and having appreciable secondary emission at the plate. The negative plate resistance can be varied by adjusting the control-grid potential. Oscillations take place when the negative plate resistance is less than the parallel-resonant resistance of the tank circuit, *L-C*. If the negative resistance is just barely low enough to start oscillation, the frequency stability in respect to tube voltages is extremely high, and the output waveform is practically sinusoidal. The simple circuit can be operated over a wide frequency range, from low audio frequencies to about 15 mc. This makes it suitable for use as a laboratory or test oscillator and other low-power applications.



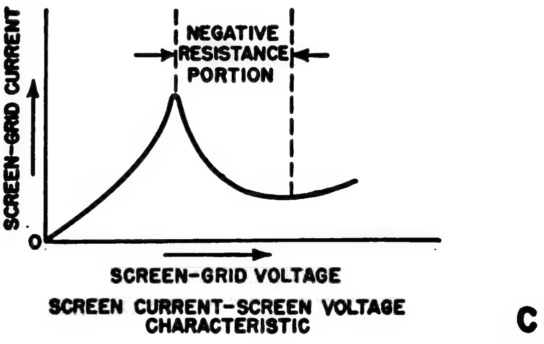
DYNATRON

A



TRANSITRON

B



SCREEN CURRENT-SCREEN VOLTAGE CHARACTERISTIC

C

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Figure 61. Negative-resistance oscillators.

b. Transitron. The negative-transconductance oscillator or transitron (B of fig. 61) takes advantage of the fact that the characteristic curve of screen current versus screen voltage of a pentode, in which the screen is coupled to the suppressor (through *C*1), has a portion with a negative slope. This negative resistance can sustain oscillations in an *L-C* tank inserted in the screen circuit. The reactance of capacitor *C*1 must be negligible compared with the resistance, R_g, at the resonant frequency of the *L-C* tank circuit. The voltage on the suppressor grid affects the division of the total space current between screen grid and plate. An increase in the suppressor-grid voltage results in a greater number of the available electrons passing through to the plate. This increases the plate current and decreases the screen current. The opposite effect also takes place. Since the reactance of *C*1 is negligible, the a-c component of the suppressor-grid voltage has the same polarity as that of the screen-grid voltage. An increase in screen voltage, therefore, causes a corresponding increase in suppressor voltage, and hence a decrease in screen current. This is the reason for the negative slope (negative resistance) apparent in C of figure 61. The transitron oscillates readily up to 15 mc and has the additional advantage over the dynatron that it does not obtain its negative resistance by secondary emission, which is relatively unstable at times.

49. Ultrahigh-Frequency Oscillators

The generation of ultrahigh frequencies (above 300 mc) involves techniques radically different from those discussed previously. It is not possible here to discuss all the factors that reduce the efficiency and power output and limit the frequency of operation of conventional electron-tube oscillators, nor is it feasible to describe the great number of special tubes and circuits that have been developed to generate microwave frequencies efficiently up to 30,000 mc or more. However, the brief discussion that follows will give some appreciation of the difficulties encountered with conventional frequency tubes and circuits when used in uhf application, and a few of the ways that have been found to overcome these problems.

a. Frequency limit of conventional oscillators. To increase the frequency of oscillation of ordinary electron-tube oscillators, it is necessary to decrease the inductance and capacitance of the oscillating tank circuit ($f=\frac{1}{2\pi}\sqrt{LC}$). In the limit, the external capacitance of the tank circuit is zero, and the tank circuit inductance shrinks to a straight conductor, short-circuiting the plate and grid terminals. The tube itself then becomes the oscillating circuit with an inductance composed of that inherent in the grid and plate leads, in parallel with the interelectrode capacitances. This upper-frequency limit is called the resonant frequency of the tube. However, even before this theoretical limiting frequency set by the physical structure of the tube is reached, it is found that above a certain high-frequency level the efficiency and power output begin to fall off rapidly, and eventually oscillations cease entirely. In addition to the effect of the inductances and capacitances associated with the tube electrodes, this drop in power output is caused by increased radio-frequency losses and the transit time of electrons between the cathode and plate.

(1) *R-f power losses.* As the frequency is raised, the r-f power losses in the oscillating circuit increase, because of—

(a) Increasing skin effect, resulting in high a-c resistance.

(b) Greater capacitance charging currents resulting from the small reactance of interelectrode and distributed capacitances at ultra-high frequencies.

(c) Dielectric losses in the tube base and glass envelope.

(d) Energy loss by direct radiation from the circuit.

(2) *Transit time.*

(a) The time taken by an electron to pass from the cathode to the plate of a vacuum tube is known as the *transit time.* At operating frequencies below 100 mc, the transit time is negligible compared with the duration of the cycle. Consequently, the output plate current can be assumed to respond instantaneously to changes in electrode voltages. As the frequency is increased above 100 mc, however, the time of passage of electrons between the cathode and plate becomes appreciable in respect to the time of a cycle. Consequently, a change in the electrode voltages no longer affects the plate current instantaneously. Changes in plate current now lag behind changes in grid voltage, just as in an inductance. In addition, the normal 180° phase difference between the plate current and plate voltage will now be greater than 180°. For good efficiency in an oscillator, the plate current must be in phase with the grid voltage, and 180° out of phase with the plate voltage. As a result of the phase shift introduced by the finite transit time, the power output decreases and plate dissipation increases. If the phase shift becomes sufficiently great, and is not corrected, the tube will not oscillate at all.

(b) The finite transit time also causes power to be consumed by the grid of the tube, even when the grid is biased negatively and attracts no electrons. This is because of the interchange of energy between the signal voltage acting on the grid and the electrons traveling to the plate. The power consumed in this way can be expressed in terms of an equivalent input resistance considered to be in parallel with the input capacity between the grid and cathode. This equivalent input resistance decreases rapidly as the frequency rises, and practically short-circuits the grid to the cathode at ultra-high frequencies. This means that the driving power required for proper grid excitation increases as the square of the frequency. Consequently, proper excitation by the grid voltage is prevented. Oscillations stop when the amplification of the tube falls to a value below that required to overcome the losses in the oscillator tank circuit. The grid power loss also raises the temperature of the tube, which is another limitation on the maximum frequency of oscillation. It has been found in practice that as a result of phase shift and grid power loss, the tube stops oscillating when the transit time approaches the time required for a quarter of a cycle at the operating frequency.

b. Barkhausen-Kurz Oscillator. The Barkhausen-Kurz oscillator (fig. 62) depends for its

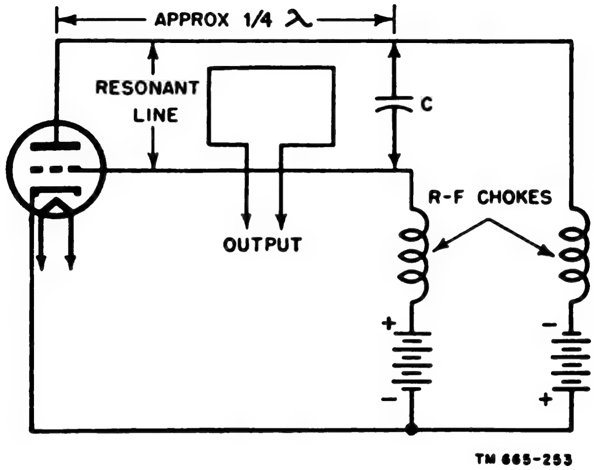

Figure 62. Barkhausen-Kurz oscillator.

action on the finite electrons transit time at ultrahigh frequencies. The frequency of oscillations in this circuit is independent of the extrenal circuit, and depends only on the transit time of the electrons and the grid voltage on the tube. As shown in the figure, a triode is utilized with the grid operated at a high positive potential, and the plate at a slightly negative potential. It is, there, fore, also known as a positive-grid oscillator.

(1) To understand the action, assume first that the grid and plate potentials are constant. Electrons emitted from the cathode are attracted toward the positive grid. A few strike the grid, but the majority pass through the spaces between the grid wires and continue toward the plate. Since the plate is negative, the electrons slow down in the space between the grid and the plate, and finally stop just short of the plate. The electrons then are drawn back toward the grid with increasing velocity. Again, a few will be captured by the grid wires, but the greater number pass into the grid-cathode space and slow down upon approaching the cathode. In this way, electrons oscillate back and forth about the grid, until they ultimately strike it by a chance impact. The frequency of the electron oscillation is determined primarily by the dimensions of the electrodes and by the grid voltage.

(2) To obtain continuous oscillation and draw power from the oscillator, it is necessary to make the electrons vibrate about the grid structure in synchronism, and to sort out or eliminate all of those electrons which do not have the proper phase. Assume now that there is superimposed on the d-c grid voltage an alternating voltage having a frequency corresponding to the time taken by an electron to travel from cathode to plate (transit time). Consider an electron that leaves the cathode at the instant when the alternating grid voltage is zero and changing from positive to negative, so that it subtracts from the d-c voltage. Now, the acceleration of the electron between cathode and grid is less than with constant grid voltage as described in (1) above. Upon passing through the grid, the electron will be slowed down even more than with constant grid voltage, since now the a-c grid voltage has reversed in polarity (it adds to the positive d-c grid voltage) and assists in drawing the electron back to the grid while the plate repels it. The electron, therefore, does not approach the plate as closely as with constant grid voltage. As it starts back toward the grid, the superimposed a-c voltage again becomes negative, thus slowing down the electron on the return trip. As a result, the electron always works *against* the superimposed a-c voltage in its round trip from cathode to plate and back. Because of the reduction in velocity, the electron gives up some of its energy to the source of the alternating grid voltage. It can be shown that electrons which leave the cathode at an instant when the a-c grid voltage becomes more positive gain energy from the a-c source and are accelerated sufficiently to strike the plate, or else strike the cathode on their return, thus being eliminated. Consequently, all electrons which would tend to suppress the oscillation because of incorrect phase are removed, and those with the proper phase oscillate back and forth until their energy is absorbed by the external resonant circuit.

(3) The resonant circuit used at ultrahigh frequencies generally consist of a pair of parallel wires. Resonance takes place

when the wires have a length of one-quarter of the wavelength corresponding to the transit time frequency. The resonant circuit is a section of transmission line which is tuned to a quarter-wavelength by the low reactance of *C* of the shorting bar. Because of the nature of the generating process, the efficiency of the Barkhausen-Kurz oscillator is low, being about 2 to 3 perent. Oscillations can be generated in a range from 30 to over 2,000 mc.

c. Klystron Oscillator.

(1) *Velocity modulation.* The operation of transit-time tubes, such as the Barkhausen-Kurz and other positive-grid oscillators, is based on the transfer of energy from moving electrons to a source of a-c voltage by the action of the electric field produced by the a-c voltage. Special means must be provided to make the energy delivered to the field of the a-c voltage exceed the energy taken from the field, since this is necessary for the tube to act as an oscillator. In the positive-grid oscillators, this is done by removing, from the space within the tube, all electrons that gain energy. This is inefficient, since the electrons first must gain energy supplied by an external voltage source, before they can be removed. More efficient operation is attained in *velocity-modulated* tubes, by making most of the electrons pass through the electric field at such times that they deliver energy to the source of the alternating electric field. This is accomplished by speeding up the electrons that would normally pass through the electric field too late, and slowing down those electrons that would normally pass through the field too soon. In this way, the electrons emitted from the cathode can be formed into compact bunches or groups. These bunches then deliver energy to the electric field on the grid and to an external resonant circuit. This principle is called velocity modulation. The klystrons is one type of velocity-modulated tube.

(2) *Klystron tube.*

(*a*) At one end of the klystron tube (A of fig. 63) is an electric gun consisting of a cathode and an accelerator grid. The electrons are emitted from the heated cathode and are attracted toward the positive accelerator grid. Most of the electrons pass through the grid wires to form a beam of electrons, all traveling at the same speed. The beam of electrons then is passed through a pair of closely spaced grids, called buncher grids, each of which is connected to one side of a tuned circuit. An alternating voltage exists across the tank circuit which speeds up or slows down the electrons, depending on when they enter the space between the grids.

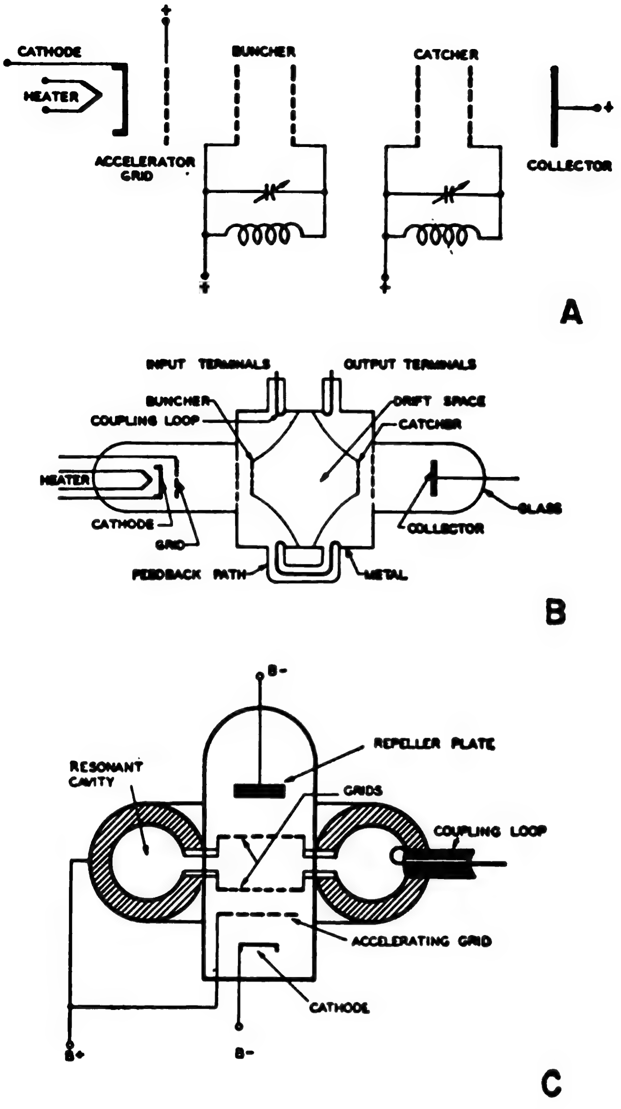

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Figure 63. Klystron oscillators.

Electrons that pass through the buncher grids at the instant when the a-c voltage is zero leave the buncher with unchanged velocity. Electrons that pass through the buncher a little earlier, when the a-c voltage is negative, are slowed down. Electrons that pass through the buncher later, when the a-c voltage is positive, are speeded up. This action causes the electrons to bunch together at some point beyond the buncher grids. Consequently, the electron stream consists of bunches of electrons separated by regions in which there are few electrons.

(*b*) These bunches of electrons pass through a second set of grids, called the catcher grids, which also are coupled to a resonant circuit. The polarity of the a-c field on the catcher grids is such that the electrons are slowed down and thereby give up some of their kinetic energy to the electric field, and, consequently, to the tuned circuit. The spent electrons are removed from the circuit by a positive collector plate. The bunches pass through the catcher at the resonant frequency of the tuned circuit (one each cycle), and so maintain a continuous alternating current in the tank circuit. Some of the energy is fed back from the tuned circuit of the catcher to the resonant circuit of the buncher in the proper phase, thus producing self-sustained oscillations. This type of klystron can be used also as an amplifier or mixer.

(*c*) For work at high frequencies, the tuned circuits of the buncher and catcher take the form of hollow metal chambers, called cavity resonators, with one of the grids attached to each side of the cavity (B of fig. 63). These cavities possess all of the properties of conventional tank circuits, but are much more efficient at ultra-high frequencies. They are so small at these extremely high frequencies that the entire cavity can be sealed within the envelope of the tube or around the outside of the envelope. Energy is extracted from or coupled into the cavities by means of single-turn coupling loops, placed within the chambers.

(*d*) For oscillator use, a simplified type of klystron which uses the same set of grids for both bunching and catching has been developed (C of fig. 63). In this *reflex klystron*, a negative repeller plate is placed beyond the grids. This serves to repel the electrons that have been bunched on their first trip through the grids. The electrons then pass back through the grids, where energy is taken from them in the same manner as in the conventional catcher. The reflex klystron utilizes a single-cavity resonator, which is more easily adjusted than the two-resonator klystron.

d. Magnetrons. The magnetron is a diode electron tube whose current is influenced by a magnetic field. As a uhf generator it can oscillate at frequencies from 300 to beyond 30,000 mc and produce peak powers of several thousand kilowatts or more. Early forms of the tube were of split-anode type (A of fig. 64), consisting of a cathode

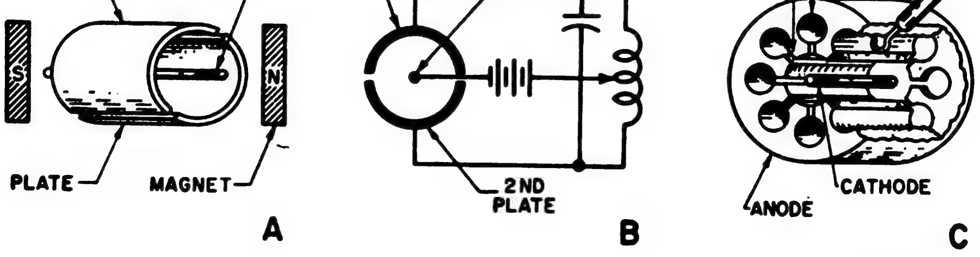

Figure 64. Magnetron oscillators.

and a cylindrical plate concentric with the cathode, and split into an even number of segments. (In A, two segments are shown.) Modern superhigh frequency magnetrons are of the transit-time type shown in C. Their construction and operation are far more complex than in the split-anode type.

(1) In the magnetron, a magnetic field is placed parallel to the tube axis and is, therefore, perpendicular to the electric field between the cathode and plate. A permanent magnet or an electro-magnet can be used to provide the magnetic field. The segments of the plate are kept at some positive potential with respect to the cathode. In the absence of a magnetic field, the electrons travel to the plate in straight paths. However, as the magnetic field is increased, the electron path becomes more and more curved, and finally circular. At a certain critical value of the field strength, the electrons miss the plate entirely and return to the cathode in a circular orbit. At higher values of the magnetic field strength, the radii of the circular orbits become smaller.

(2) When the plate segments are made part of a resonant circuit, as in A of Figure 64, and the magnetic field is adjusted so that the electrons just fail to reach the plate, uhf oscillations are produced. The action is somewhat analogous to the positive-grid oscillator, and depends upon the transit time of the electrons. An alternating voltage, created by the resonant circuit, is superimposed on the constant voltage present on the plate segments. This causes the plate voltage to vary about its d-c value. If the period of the a-c voltage is made equal to the transit time of an electron for a complete circular rotation, some electrons will be slowed down by the alternating field at the plate and lose energy to it; others will be speeded up, and thus gain energy from the a-c electric field. The tube can be adjusted so that energy is extracted by the electric field from a majority of electrons grazing the plates. This energy sustains powerful oscillations in the associated resonant circuit. The frequency of oscillation is determined primarily by the the transit time of the electrons. The magnetron also can be operated as a negative-resistance oscillator at frequencies that are low compared with the transit-time frequency. In this type of operation, the frequency can be varied continuously by changing the constants of the resonant circuit.

(3) The anode assembly of the superhigh frequency magnetron is a block of copper, which assists in heat dissipation. The cathode is a cylinder located at the center of the structure. Radial slots in the anode lead out from the cathode region to circular holes. Each slot and terminating hole is electrically equivalent to a tuned circuit. Under proper conditions of anode voltage and magnetic field strength, energy is transferred from the swarm of electrons which moves toward the anode, and powerful oscillations are sustained in the resonant circuits. The oscillations can be coupled to the output by means of a wire loop placed in one of the circular holes. A cutaway view of a magnetron is shown in figure 65.

50. Summary

a. Every oscillating system has two elements, inertia and elasticity, capable of storing and releasing energy from one to the other at a natural frequency determined by the dimensions of the elements.

b. A continuous or self-oscillator has three main components—an oscillating system, consisting of two elements that are capable of storing and releasing energy; a unidirectional source of energy that can replenish the energy lost in the oscillator because of internal resistance; and a synchronous mechanism that can release energy from the source at the proper time during each cycle to assist the oscillation.

c. Energy in a tank circuit is stored alternately in the electric field of the capacitor and the magnetic field around the coil. The frequency of natural oscillations in a tank circuit is approximately $\underline{f = 1/2\,\pi,}\ \sqrt{LC}$

d. An electrical oscillator acts as an energy converter which changes d-c energy into a-c energy.

e. Vacuum tubes can be used as efficient oscillators, because of their ability to amplify. The

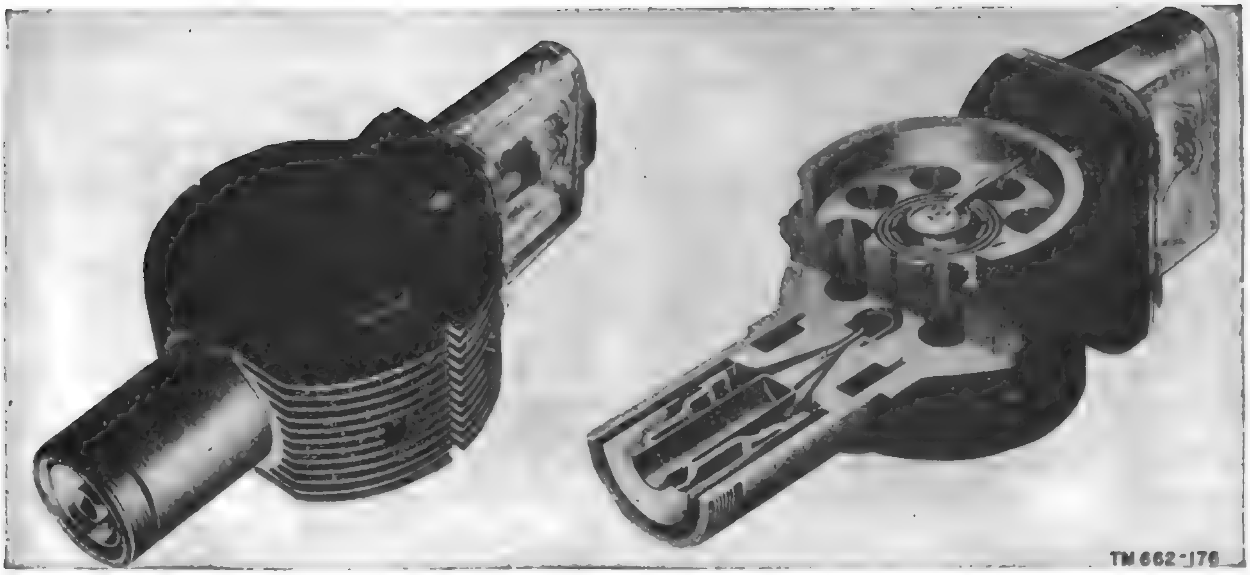

Figure 65. Operational and cutaway view of typical magnetron.

essential parts of a triode oscillator are an oscillatory tank circuit, containing L and C, to determine the frequency of oscillation; a source of energy to replenish losses in the tank circuit; and a feedback circuit for supplying energy from the source in the right phase to aid the oscillation.

f. The amplification factor of the tube and the amount of energy fed back must be sufficient to overcome all circuit losses. If losses are overcome completely, the effective circuit resistance is zero, and oscillations take place. Positive feedback, or regeneration, takes place when the voltage fed back is in phase with the voltage in the grid circuit.

g. In the tickler feedback oscillator, positive feedback occurs because of mutual induction between the tickler and the tank coils.

h. Grid-leak bias is used in oscillators to make the oscillator self-starting and to insure stable operation.

i. The Hartley oscillator is a modified version of the tickler feedback circuit, using a tapped coil rather than two separate coils.

j. In a series-fed oscillator, both the d-c plate current and the alternating component of the plate current flow through a common circuit. In a parallel-fed oscillator, the plate circuit is divided into two parallel branches, one of which carries the direct current and the other the alternating current (r-f).

k. The Colpitts oscillator is similar to the Hartley circuit, except that it uses a split capacitor in place of the tapped coil. The tank-circuit capacitors act as a simple voltage divider.

l. The Meissner oscillator is similar to the Hartley circuit, except that the tank circuit is floating and is not directly connected to the plate and grid circuits. The tank coil serves as an inductive coupling or link circuit between the plate-circuit coil and the grid-circuit coil.

m. The tuned-plate, tuned-grid oscillator uses a tuned tank circuit in both the grid and the plate circuits. Feedback in the TPTG oscillator takes place entirely through the grid-to-plate capacitance of the tube. Both the grid and plate tank circuits must be tuned to a frequency slightly higher than the desired operating frequency.

n. The natural frequency of oscillation is influenced by all factors which affect the tank-circuit inductance and capacitance, as well as those which affect the effective series resistance of the tank circuit and the a-c plate resistance of the tube. Some of these factors are changes in tube characteristics, changes in temperature, vibration, and changes in load.

o. Large power output from an oscillator and good frequency stability are mutually incompatible.

p. In an electron-coupled oscillator a common electron stream couples the load to the oscillator section. This minimizes the effect of the load on the frequency of oscillation. A single tube (tetrode or pentode) fulfills the functions of a triode oscillator and an amplifier.

q. The control of frequency by means of crystals is based on the piezoelectric effect. Quartz is the most suitable piezoelectric crystal because it is cheap, mechanically rugged, chemically inert, and expands very little with heat.

r. The temperature coefficient of a crystal is the shift in its resonant frequency, expressed in cycles per megacycle, for an increase in temperature of 1° C. X- and Y-cuts have a poor temperature coefficient, while AT- and BT-cuts have zero temperature coefficient at certain temperatures.

s. At its frequency of mechanical resonance, a quartz crystal behaves exactly like a tuned circuit.

t. The advantages of crystal oscillators are extreme sharpness of resonance curve and high effective Q, good frequency stability, and their value as frequency standards because of harmonic output.

u. The limitations of crystal oscillators are fixed frequency of operation and relatively low power output because of crystal heating and danger of fracture.

v. The Pierce crysal oscillator is similar to the Colpitts circuit, with the crystal replacing the tank coil, and the tube interelectrode capacitances substituting for the tank capacitors.

w. The tri-tet oscillator combines the principles of a triode crystal oscillator with those of electron-coupled oscillators, and has some of the advantages of both.

x. The dynatron oscillator uses a tetrode operated with the plate less positive than the screen and having appreciable secondary emission at the plate. It makes use of the negative resistance characteristic of a tetrode to overcome the losses in the tank circuit, and thereby generates oscillations.

y. The transitron, or negative-transconductance oscillator, makes use of the negative resistance exhibited by the screen-current, screen-voltage characteristic of a pentode, in which the screen is coupled to the suppressor grid. This negative resistance can sustain oscillations in a tank circuit inserted in the screen circuit.

z. The frequency of conventional oscillators is limited by the inductances and capacitances associated with the tube electrodes, increased r-f power losses as the frequency increases, and the transit time.

aa. The Barkhausen-Kurz oscillator is a positive-grid oscillator, capable of generating ultrahigh frequencies. The frequency of oscillations is independent of the external circuit, and depends primarily on the transit time of the electrons and the grid voltage.

ab. The klystron is based on the principle of velocity modulation, which forms the electrons emitted by the cathode into compact bunches, capable of delivering energy to the electric field on the catcher grids. If feedback is provided, uhf oscillations can be generated. A reflex klystron uses the same set of grids for both bunching and catching in conjunction with a negative repeller plate which reflects the electrons. Reflex klystrons are used as uhf oscillators.

ac. A magnetron is a diode whose plate current is influenced by a magnetic field which is at right angles to the electric field between the plate and cathode. Powerful microwave oscillations can be generated by means of this tube.

51. Review Questions

a. Describe the three main components of a continuous oscillator, and state what determines the frequency of oscillations.

b. Explain how energy is stored in a tank circuit.

c. What is the natural frequency of oscillations in a tank circuit?

d. A radio cabinet rattles strongly when a singer reaches a certain note. Explain. State similar cases from your experience.

e. What is the ratio of energy stored to the energy lost per cycle in a tank circuit, which has a resistance of 2 ohms, an inductance of 5 μh, and a capacitance of 500 $\mu\mu$f?

f. Explain the *flywheel action* of a tank.

g. Why is a vacuum tube not an oscillator in itself?

h. What are the essential parts of a triode oscillator? State the conditions for oscillation.

i. Why must the voltage feed back be in phase with the grid voltage? How is feedback obtained in the tickler feedback oscillator?

j. The output waveform of an oscillator is distorted badly. What conditions could cause this?

k. Why is grid-leak bias used in most oscillators?

l. Why is more power obtained from an oscillator when operated class C?

m. When the electrode voltages are applied to a power oscillator, the oscillations start out with a very tiny amplitude and build up to an equilibrium value. Explain why the oscillations do not continue to build up indefinitely. Why is the equilibrium stable?

n. Explain the operation of a series- and a parallel-fed oscillator. What are the advantages of each?

o. In a Colpitts oscillator, the tank coil has an inductance of 10 μh, tank capacitor $C1=700$ μμf, and tank capacitor $C2=.0021$ μf. What is the frequency of oscillation? What fraction of the total voltage across the tank is applied across the grid?

p. What is the function of the floating tank coil in the Meissner oscillator?

q. If the grid-tank circuit of a TPTG oscillator is tuned to a frequency of 1,260 kc and the plate tank is set to 1,259 kc, will the circuit oscillate? Explain. What should be done?

r. Define frequency stability. Why is it desirable to have good frequency stability?

s. State four primary causes for frequency instability and drift. How are these causes affected in turn by other conditions? What are some of the methods used to insure frequency stability?

t. What is the effect of overloading an oscillator?

u. Explain three ways in which an oscillator can be coupled to a load.

v. What makes frequency doubling possible in electron-coupled oscillators?

w. Describe various types of piezoelectric crystals and explain why quartz is the most satisfactory piezoelectric material for general use.

x. Explain the orientation of the X-, Y-, and AT- cuts in respect to the crystal axes.

y. What are the factors limiting the highest frequency that can be generated by a crystal?

z. Define temperature coefficient. Calculate the frequency drift for an X-cut crystal operating at 9 mc, if the temperature increases from 20 to 40° C.

aa. Why are crystal oscillators used in many commercial and military installations? Describe some of their advantages and limitations.

ab. Explain the principles on which negative-resistance oscillators are based. How do the dynatron and the transitron differ?

ac. Explain the factors limiting the highest usable frequency of conventional oscillators.

ad. How does a positive-grid oscillator operate? What determines its frequency of oscillation?

ae. What is the principle of velocity modulation?

af. What are two special tubes which are used as uhf oscillators?

CHAPTER 4

CONTINUOUS-WAVE TRANSMISSION

52. Transmission of Information by Radio

a. Purpose of Transmitter. The purpose of the radio transmitter is to produce r-f energy, and with its associated equipment to radiate a useful signal. Any of the oscillators described in chapter 3 may be used to generate a steady flow of r-f energy. The transmitted high-frequency power is called the *carrier wave*, or simply the *carrier.*

b. Methods of Conveying Information.

(1) Since the carrier by itself does not convey any intelligence, information to be transmitted must be added to the carrier. The process of adding or superimposing information on the carrier is called *modulation.*

(2) Radiotelegraph information can be transmitted by starting and stopping the carrier by means of a switch, which is opened and closed to control the flow of power to the transmitter. A telegraph key or an automatic code machine usually is substituted for the switch. Messages can be sent by means of short and long pulses (dots and dashes) which correspond to letters and numerals of the radiotelegraph code. When the operator closes or presses the key down, the carrier wave is sent out from the antenna. When the key is raised or opened, the carrier is cut off. If the operator wishes to send the letter A in code, he closes the key for a fraction of a second, opens it for the same length of time, then closes it again for a period of time three times the length of the first. The length of a dash is three times the length of a dot. Spacing between dots or dashes within a letter or numeral is equal to the length of one dot (fig. 66). Spacing between letters in a word is equal to three dots or one dash. This process of transmitting information in the form of dots and dashes is called *radiotelegraphy.*

(3) The human voice or a wide range of sound frequencies—for example, a symphony orchestra—can be transmitted by radio. This form of transmission is called *radiotelephony.* A sensitive microphone picks up the sound and converts the sound waves into audio-frequency voltages. These voltages then are fed to a modulator which superimposes the audio-frequency signal on the carrier wave.

(4) *Facsimile* is the transmission of printed or written matter, maps, charts, and other similar data by radio. The printed mat-

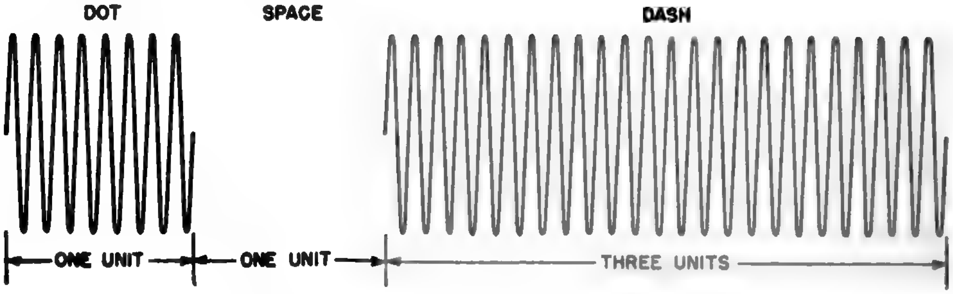

Figure 66. Dot and dash in radiotelegraph code.

ter is placed on a rotating drum in the transmitter. Light is reflected from the light and dark areas on the copy, converted to electrical impulses, amplified, then transmitted by radio. The facsimile receiver converts the signal back to its original form. At the destination, the intensity of a tiny spot of light, controlled by the received voltages, affects a sensitized paper on a rotating drum in the receiver. After being treated with a chemical process similar to photographic developing, the paper becomes a duplicate or facsimile of the printed matter at the transmitter. This is not an instantaneous process. Some equipment requires 20 minutes to reproduce a 12- by 17½-inch photograph.

(5) *Television* is another application of radio. This is a process of transmitting and receiving over great distances continuous, instantaneous pictures of events. In addition to viewing the action, the observer hears speech and other sounds occurring at the place of action by means of a radiotelephony channel adjacent to the television picture channel.

c. Need for Carrier Wave. When any alternating current is passed through a conductor, an electromagnetic field is radiated. This principle forms the basis of a transmitting antenna. It would seem that information could be transmitted by feeding a signal, from a microphone or other pickup device, directly into the antenna. This is impractical for two reasons—The amount of electromagnetic energy radiated from an antenna for a given power input decreases with a decrease in frequency. The amount of power required for direct transmission of audio frequencies over reasonable distances is prohibitive. Even if it were practical to radiate signals at audio frequencies, all stations would interfere with each other so that only one would be able to transmit at a time. The use of a radio-frequency carrier wave excludes the limitations mentioned above. Radio-frequency carriers can be spaced every 10 kc for broadcast stations and even closer for c-w (continuous-wave) and radiotelephone communication circuits.

d. Radio-Frequency Spectrum.

(1) The assignment of a radio transmitter to a definite band of the r-f spectrum depends on many considerations. To avoid confusion, international conferences are held from time to time to assign frequencies for definite applications. Specific channels or bands are provided for marine, aeronautical, and navigational aids, standard broadcast, amateur radio, military services, international shortwave broadcasts, and miscellaneous services. Also taken into consideration are the effective transmitting range for a given transmitting power, freedom from interference by other services, and effects of seasonal changes on transmitting range and receiving conditions.

(2) Frequencies below 100 kc usually provide reliable communication for 24 hours a day without being subjected to interference by magnetic storms. Many stations engaging in international communications operate in this sector of the spectrum. Extremely large antennas are required, some of which are several miles long.

(3) Frequencies between 100 and 500 kc are allocated to marine communications, aircraft beacons, and miscellaneous services. The band is suitable for medium- and long-range communication. Antennas are usually large. The size of antennas decreases as the frequency increases.

(4) American broadcast stations are assigned frequencies between 550 and 1600 kc. The transmitting range of stations in this band varies with the time of day and usually is limited to a few hundred miles. Frequencies in this band are assigned to other services in some foreign countries.

(5) Frequencies between 1600 and 6000 kc are suitable for reliable short- and medium-range communication circuits. World-wide communication is possible but under rather unpredictable conditions. Military services, amateur, police, marine, aeronautical, and miscellaneous services have frequencies in this range. Communication circuits are fairly reliable both day and night.

(6) International shortwave broadcasts, commercial circuits, the armed forces, police, marine, and other services use

frequencies in the 6- to 30-mc range when long-range communications are desired for given periods during the day or night. As the frequency increases, the transmitting range varies sharply during different hours.

(7) Frequencies above 30 mc are used widely for short-range circuits. Variations with atmospheric conditions and time of day make long-range contacts between fixed locations unreliable. Communication circuits usually are based on line-of-sight transmission with the range limited to a few miles beyond the horizon or the most distant point that can be seen from the top of the transmitting antenna. Television, frequency modulation, radar, experimental broadcasts, the armed forces, point-to-point stations, public utilities, police and fire departments, and numerous other services operate in the frequencies above 30 mc. The radio-frequency spectrum between 10 kc and 30,000 mc together with the classification of each band is shown in figure 67.

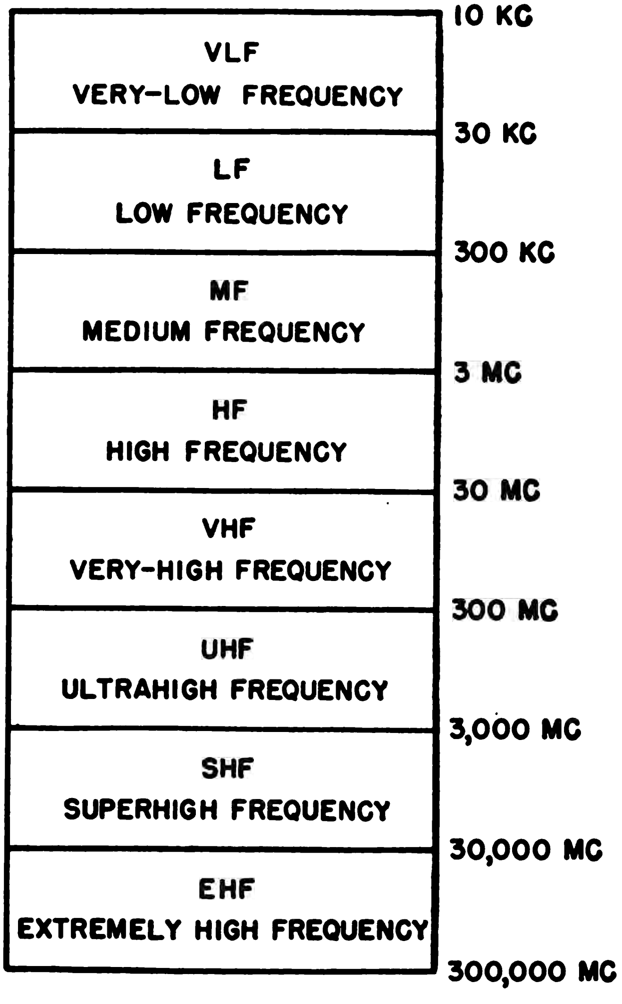

Figure 67. R-f spectrum.

e. Modulation. When a-f signals are superimposed on the r-f carrier, additional r-f signals are generated. The additional frequencies are equal to the sum and difference of the audio frequencies and the radio frequency involved. For example, assume that a 1000-kc carrier is modulated by a 1-kc audio tone. Two new radio frequencies are developed, one at 1001 kc (the sum of 1000 and 1 kc) and the other at 999 kc (the difference between 1000 and 1 kc). If a complex audio signal is used instead of a single tone, two new frequencies will be set up for each of the audio frequencies involved. The new frequencies are called sideband frequencies.

53. Classification of Emissions

a. Radio-wave emissions have been classified by international agreement depending on the type of modulation used. The ITRC (International Telecommunication and Radio Conference) which met in Cairo in 1938 devised the following classification for amplitude-modulated continuous (undamped) waves:

Designator	*Type of emission*
A0	Waves the successive oscillations of which are identical under fixed conditions.
A1	Telegraphy on pure continuous waves. A continuous wave that is keyed according to a telegraph code.
A2	Modulated telegraphy. A carrier wave modulated at one or more audible frequencies, the audible frequencies or their combination with the carrier wave being keyed according to a telegraph code.
A3	Telephony. Waves resulting from the modulation of a carrier wave by frequencies corresponding to the voice to music or to other sounds.
A4	Facsimile. Waves resulting from the modulation of a carrier wave by frequencies produced by the scanning of a fixed image with a view to its reproduction in a permanent form.
A5	Television. Waves resulting from the modulation of a carrier wave by frequencies produced at the time of the scanning of fixed or moving objects.

b. The foregoing classification of emissions is still widely used, but is inadequate since there is no provision for systems such as frequency modulation, pulse-time modulation, frequency-shift keying and multiplexing. The International Telecommunication and Radio Conference which met at Atlantic City, New Jersey, in 1947 adopted a new system which was more comprehensive and overcame the deficiencies of the previously adopted system. This system classifies emissions according to type of modulation, type of transmission, supplementary characteristics, and bandwidth as follows:

Types of modulation	*Symbol*
Amplitude	A
Frequency (or phase)	F
Pulse	P
Types of transmission	
Absence of any modulation intended to carry information	0
Telegraphy without the use of modulating audio frequency	1
Telegraphy by the keying of a modulating audio frequency or audio frequencies or by keying of the modulated emission	2
Telephony	3
Facsimile	4
Television	5
Composite transmissions and cases not covered by the foregoing	9
Supplementary characteristics	
Double side band, full carrier	None
Single side band, reduced carrier	a
Two independent side bands, reduced carrier	b
Other emissions, reduced carrier	c
Pulse, amplitude-modulated	d
Pulse, width-modulated	e
Pulse, phase- or position-modulated	f
Bandwidth	
Bandwidth is indicated by a prefix giving the bandwidth in kilocycles.	

c. Following are typical examples of the new ITRC designators:

Designator	*Type of emission*
0.1 A1	Telegraphy; 25 words per minute, International Morse Code, carrier modulated by keying only.
3 A3a	Amplitude-modulated telephony; 3,000 c/s maximum modulation, single-side band, reduced carrier.
46 F3	Frequency-modulated telephony; 3,000 c/s modulation frequency, 20 000 c/s deviation.

54. Simple Electron-Tube Transmitter

a. A simple one-tube c-w transmitter can be made by coupling the output of an oscillator directly to an antenna (fig. 68). The primary purpose of an oscillator is to develop an r-f voltage which has a constant frequency and is immune to outside factors which may cause its frequency to shift. The output of this simple transmitter is controlled by connecting a telegraph key at point K in series with the B-voltage supply. Since the plate supply is interrupted when the key is open, the circuit oscillates only as long as the key is closed. Although the transmitter illustrated uses a Colpitts oscillator, any of the oscillators previously described can be used.

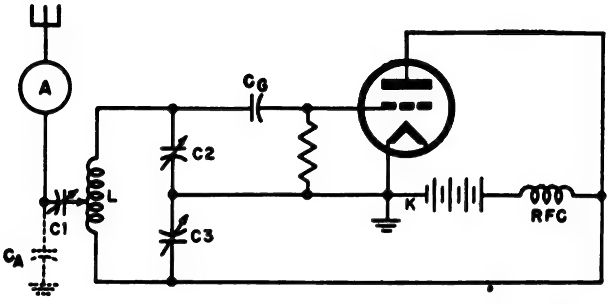

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Figure 68. Simple electron-tube transmitter.

b. Capacitors *C*2 and *C*3 may be ganged together to simplify tuning. Capacitor *C*1 is used to tune (resonate) the antenna to the transmitter frequency. C_A is the effective capacitance existing between the antenna and ground. This antenna-to-ground capacitance is in parallel with the tuning capacitors, *C*2 and *C*3. Since the antenna has capacitance, any change in its length or position, such as that caused by swaying, changes the value of C_A and causes the oscillator to change frequency.

55. Multitube Transmitters

a. General.

(1) The simple one-tube transmitted shown above rarely is used in practical equipment. Most transmitters use a number of tubes or stages. The number of tubes or stages that are used depends on the frequency, power, and application of the equipment. In this chapter, c-w transmitters in the following categories are discussed: master-oscillator power-amplifier (mopa) transmitters, multistage high-power transmitters, and high-frequency and very-high frequency transmitters.

(2) The mopa is an oscillator and a power amplifier. In order to increase power and raise the frequency, it is necessary to use additional power-amplifying stages and frequency-multiplying stages. The main difference between many low- and high-power transmitters is in the number of power-amplifying stages that are used. Similarly, the main difference between many low-frequency and high-frequency transmitters is in the number of frequency-multiplying stages used.

b. Master-Oscillator Power Amplifier (fig. 69).

(1) For a transmitter to be stable, its oscillator must not be loaded down, which means that its antenna must not be connected directly to the oscillatory circuit. To obtain good frequency stability, therefore, it is necessary to send the r-f oscillations through another circuit before they are fed into the antenna. This additional circuit is an r-f power amplifier. Its purpose is to raise the level of r-f oscillations of the oscillator to the required output power level. Any transmitter consisting of an oscillator and a single amplifier stage is called a master-oscillator power-amplifier transmitter. Not shown in the block diagram is a special network, called interstage coupling, which consists of a combination of inductance, capacitance, and, sometimes, resistance, which is used to effect efficient transfer of energy from the oscillator to the power amplifier.

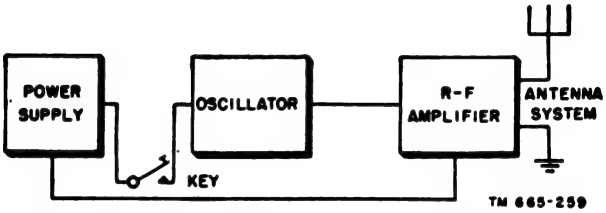

Figure 69. Block diagram of master-oscillator power-amplifier transmitter.

(2) Most mopa transmitters have only one tube in the power-amplifier stage. However, the oscillator may not produce sufficient power to drive a power-amplifier tube large enough to deliver the required power output to the antenna. In such cases, the power-amplifier stages often are designed to use two or more tubes which can be driven by the oscillator. Two or more tubes can be connected in in parallel (with similar elements of each tube connected), or in push-pull. In a push-pull amplifier, the grids are fed equal r-f voltages 180° out of phase.

(3) One advantage of a mopa transmitter is that the power-amplifier stage isolates the oscillator from the antenna and prevents changes in antenna-to-ground capacitance from affecting the frequency. A further advantage is that the r-f power amplifier is operated so that a small change in the voltage applied to its grid circuit will produce a large change in the power developed in its plate circuit.

(4) R-f power amplifiers require that a specified amount of power be fed into the grid circuit in order that the tube can deliver a given power output. Since there are limits to the amount of power that can be supplied by a stable oscillator, there is a corresponding limit to the amount of power that can be developed by a mopa transmitter. This is one of the disadvantages of the mopa transmitter. A further disadvantage is that it often is impractical for use at very-high and ultrahigh frequencies. The reason for this is that the stability of self-excited oscillators decreases rapidly as the operating frequency increases. Circuit tuning capacitances are small at high frequencies so that stray capacitances have a greater effect on the over-all frequency. Crystal-controlled oscillators are not suitable for use at very-high frequencies because such crystals are too thin and fragile to be practical.

c. Multistage High-Power Transmitters. The power amplifier of a high-power transmitter may require far more driving power than can be supplied by an oscillator. One or more low-power intermediate amplifiers may be inserted between the oscillator and the final power amplifier which feeds the antenna. In some types of equipment, a voltage amplifier, called a *buffer*, is used between the oscillator and the first intermediate amplifier. The ideal buffer is operated class A and, therefore, is biased sufficiently negative to prevent grid current flow during the excitation cycle. Therefore, it does not require driving power from the oscillator and thus does not load down the oscillator. Its purpose is to isolate the oscillator from the following stages and to minimize changes in oscillator frequency that occur with changes in loading. A buffer is essential when keying takes place in an intermediate amplifier or final amplifier operating at comparatively high power. In the block diagrams of several medium-frequency transmitters in figure 70, the input and output powers are given for each stage. It is shown that the power output rating of a transmitter can be increased by adding amplifier tubes capable of delivering the power required.

d. High-Frequency and VHF Transmitters.

(1) Oscillators are too unstable for direct frequency control in very-high frequency and ultrahigh-frequency transmitters. Therefore, these transmitters have oscillators operating at comparatively low frequencies, sometimes as low as one-hundredth of the output frequency. The oscillator frequency is raised to the required output frequency by passing it through one or more frequency multipliers. Frequency multipliers are special r-f power amplifiers which multiply the input frequency. In practice, the multiplication factor is seldom larger than five in any one stage. The block diagram of a typical vhf transmitter designed for continuous tuning between 256 and 288 mc is shown in figure 71. The stages which multiply the frequency by two are doublers; those which multiply by four are quadruplers.

(2) The oscillator is tunable from 4 to 4.5 mc. The multiplier stages increase the frequency by a factor of 64 by multiplying successively by four, four, two, and two. In high-power high-frequency transmitters, one or more intermediate amplifiers may be used between the last

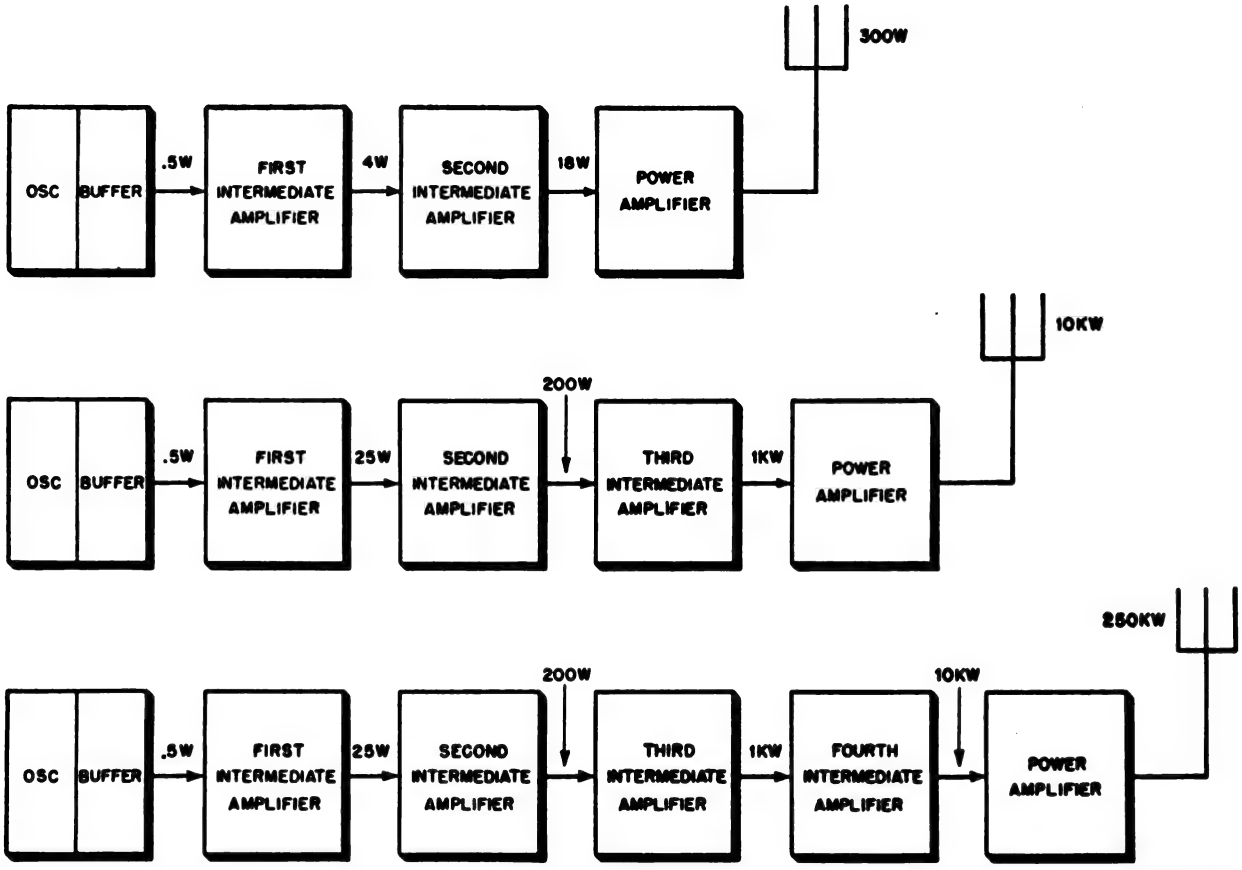

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Figure 70. Block diagram of several medium-frequency transmitters.

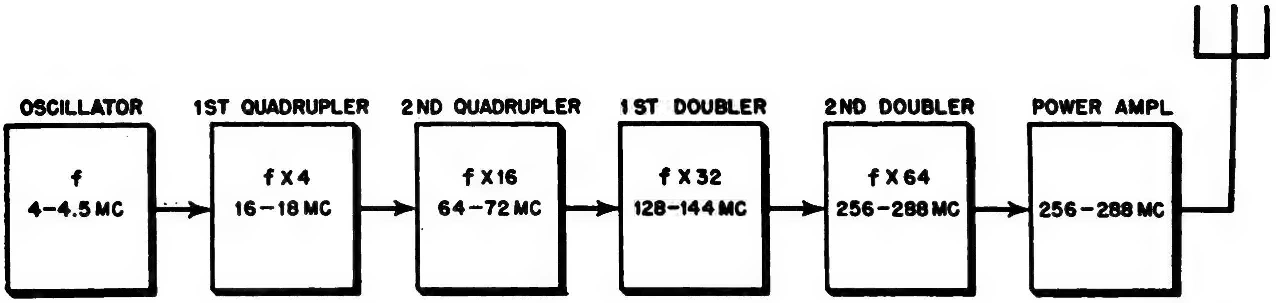

Figure 71. Block diagram of vhf transmitter.

frequency multiplier and the power amplifier. Interstage coupling networks are used between all stages within a transmitter having more than one stage.

56. Amplifiers for Radio Frequencies

a. Classes of Power Amplifiers. R-f amplifiers are divided into three classes which may be identified by the conditions under which each operates. The classifications are class A, class B, and class C. The choice of a specific type of operation is based on the circuit application. Class A operation is used for voltage amplifiers in r-f buffer stages and in audio amplifiers. Class B amplifiers sometimes are used in intermediate power amplifier applications and also for final power amplifiers when low level modulation is utilized. Class C amplifiers find widest application as frequency multipliers, intermediate amplifiers, and final power amplifiers.

b. Class A Amplifier. A class A amplifier is one in which the waveshape of the output voltage is the same as that of the signal applied to the grid of the tube. The only difference between the input and output signals is in the relative amplitudes. The operating bias is such that plate current flows for the entire excitation cycle. Since the grid is not driven positive, little or no grid current flows. Consequently, negligible driving power is required. The place circuit efficiency of the class A amplifier is approximately 25 percent.

c. Class C Power Amplifier.

(1) Class C power amplifiers are operated with grid bias two to three times greater than that required to cause plate-current cut-off. The signal applied to the grid must be large enough to overcome the bias and produce pulses of current in the plate circuit. The efficiency of the circuit increases as the duration of the plate-current flow is decreased. By making the plate-current pulse sufficiently short, circuit efficiency can be made to approach 100 percent. However, shortening the duration of plate-current flow also can reduce the input power and, consequently, the output power, even though the output is obtained at high efficiency. Therefore, as a compromise between power output and efficiency, class C amplifiers usually are operated so that the plate current flows for about 120° to 170° of the cycle. Under these conditions, the circuit efficiency is between 60 and 80 percent.

(2) When the plate-current pulse occurs, it stores energy in the plate tank circuit. As soon as the high grid bias cuts off the plate current, an oscillation starts in the tank circuit. The tank circuit may be considered shock-excited by the pulses of current and oscillating at its natural frequency between pulses. The effect of storing energy in the tank circuit is similar to the action of the flywheel on a single cylinder gasoline engine. When the gasoline is fired, the piston moves down and stores enough energy in the heavy flywheel to keep the engine turning over until the gasoline is fired on the next cycle. In amplifier circuits, the tuned-plate tank circuit corresponds to the flywheel. This action is called the flywheel effect. In addition to the fundamental, or input, frequency, many higher order harmonics are present in the pulses of current applied to the tank circuit. However, the action of the tuned tank attenuates the undesired harmonic com-

ponents and restores the sinusoidal waveform to the voltage output.

(3) For maximum output, a specified amount of driving power or excitation must be applied to the grid of a class C amplifier. Because of losses in the driver plate circuit and in the interstage coupling network, the driver stage must be capable of delivering considerably more power than required to drive the amplifier. Therefore, if a class C amplifier requires 20 watts of drive (driving power) the driver stage must deliver about 35 to 40 watts.

(4) A class C amplifier sometimes is operated as a push-pull stage. The grids of the push-pull stage are fed 180° out of phase. The signal voltage is positive on the grid of one tube at the instant that it is negative on the grid of the other. The plate tank circuit is triggered into oscillation by the plate-current pulse from the tube having the positive grid. The other tube in the push-pull circuit does not conduct at this time because the excitation voltage has driven its grid even more negative. When the signal voltage reverses, the first tube is cut off and the second tube delivers its pulse to the plate tank circuit. Therefore, the push-pull tank circuit receives a pulse during each half cycle of the excitation voltage. A push-pull circuit is used in r-f power output applications to develop a balanced voltage output waveform and to effect an increase in power output. Tubes connected in push-pull reduce the generation of the undesirable second harmonic frequency.

d. Class B Amplifiers. The essential difference between class B and class C amplifiers is in the value of the d-c bias voltage. In a class B amplifier, the grid bias is approximately equal to the cut-off value, so that the plate current is near zero when no excitation is applied. Plate current flows during the positive half of the input cycle. By careful adjustment of the driving power, the class B amplifier develops a plate-current pulse that is a replica of the positive half cycle of the input signal. The flywheel effect of the tank circuit develops a sine wave in the plate tank circuit that is an image of the input signal. The efficiency of a class B amplifier is not over 40 to 45 percent. The final power amplifier is operated as a class B amplifier when low level modulation is used.

57. Interstage Coupling Systems

a. Necessity for Interstage Coupling. Interstage coupling circuits are necessary to insure that the required amount of r-f energy is transferred from one electron tube stage to another. For maximum efficiency, the energy must be transferred with a minimum amount of power loss and a minimum amount of loading on the oscillator or driver stage. The interstage coupling system should also provide a minimum of stray coupling between stages. This stray coupling can be either electrostatic or electromagnetic. In a transmitter, the types of commonly used interstage coupling circuits are capacitive, impedance, and inductive (transformer).

b. Capacitive Coupling.

(1) A series fed plate and parallel fed grid circuit is shown in A of figure 72. The d-c supply for the plate *V*1 is in series with the tank coil and the d-c (bias) supply for the grid of *V*2 is in parallel with the tank coil. In the parallel fed plate and series fed grid circuit shown in B, the plate supply of *V*1 is in parallel with the tank circuit, which is in series with the d-c supply for the following grid.

(2) These circuits operate in a similar manner. The voltage developed across tank coil *L*1 divides across capacitors *C*1 and *C*2 in proportion to their reactances. The larger voltage is developed across the smaller capacitance. The voltage developed across *C*2 is applied to the grid of *V*2. The amount of excitation (r-f grid voltage) applied to *V*2 can be increased by decreasing the value of *C*2. Since the tank circuit is tuned by *C*1 and *C*2 in series, any change in the value of *C*2 must be counteracted by changing the value of *C*1 in the opposite direction. In each case, the r-f choke RFC provides a load for the signal.

(3) An advantage of this type of coupling is that it is possible to provide a continuous variation in the load. Furthermore, it makes it possible to vary the grid excitation voltage over a wide range. A dis-

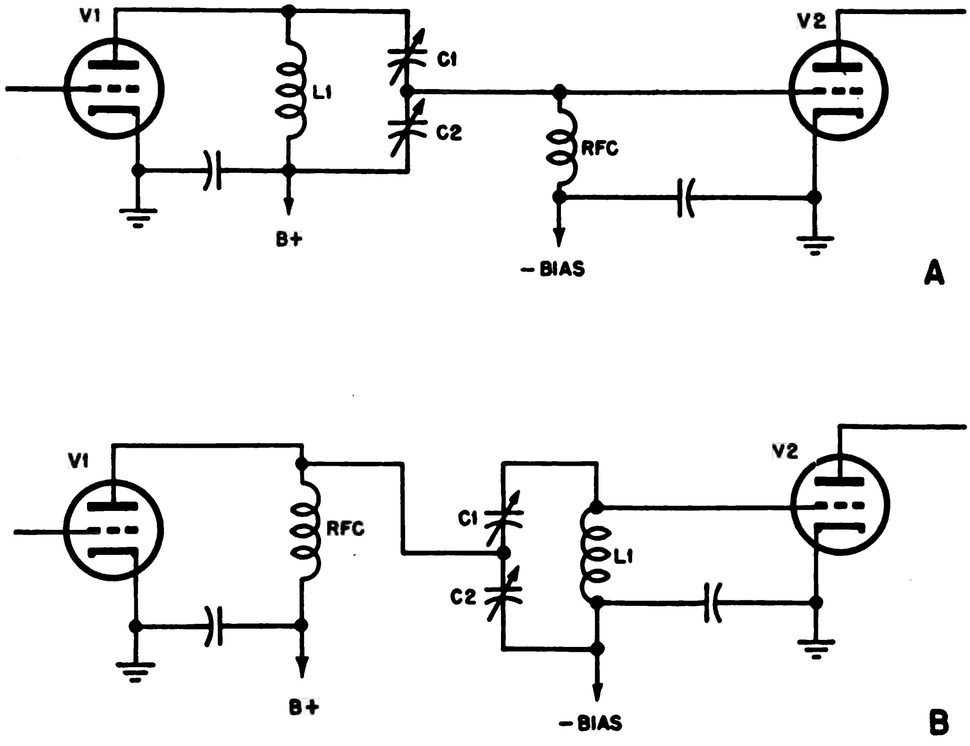

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Figure 72. Capacitive coupling circuits.

advantage is that the tuning range is limited.

c. Impedance Coupling.

(1) In the circuits shown in figure 73 as examples of impedance coupling, tank coil *L* is tapped so that the voltage applied to the grid of *V2* can be varied. Capacitor *cc* feeds r-f voltage to the grid of *V2* while preventing the passage of d-c. Because of the use of the coupling capacitor, this arrangement is sometimes referred to as capacitive coupling and the circuits shown can be called mutual capacitance couplings.

(2) In A of figure 73, the plate circuit of *V1* is series fed whereas the grid circuit of *V2* is shunt fed. In B, the plate circuit of *V1* is shunt fed and the grid circuit of *V2* is series fed.

(3) In another type of impedance coupling (fig. 74), untuned impedances (radio-frequency chokes) are used. The advantages of this circuit arrangement are low cost and minimum space requirements. A disadvantage is that the absence of a tuned circuit between stages makes it possible for the driver to feed unwanted harmonic frequencies into the amplifier where they are amplified along with the fundamental. Although the harmonic may be considerably weaker than the desired signal, it can be strong enough to cause serious interference to other stations. Furthermore, the indiscriminate use of r-f chokes or tapped coils can cause low-frequency parasitic oscillations at a frequency different from the frequency the stage is designed to pass.

d. Inductive Coupling (fig. 75).

(1) In these examples of inductive or transformer-coupling circuits, *L1* and *L2* are close together and wound in such a way that the lines of force from *L1* cut the turns of *L2* and induce a voltage in it. In the series fed circuit, in A, and the parallel fed circuit, in B, *L1* and *L2* are tuned to resonance by capacitors *C1* and *C2* respectively.

(2) Coupling between *L1* and *L2* can be varied by changing the spacing between them or by changing the angle of one coil in respect to the other. In some applica-

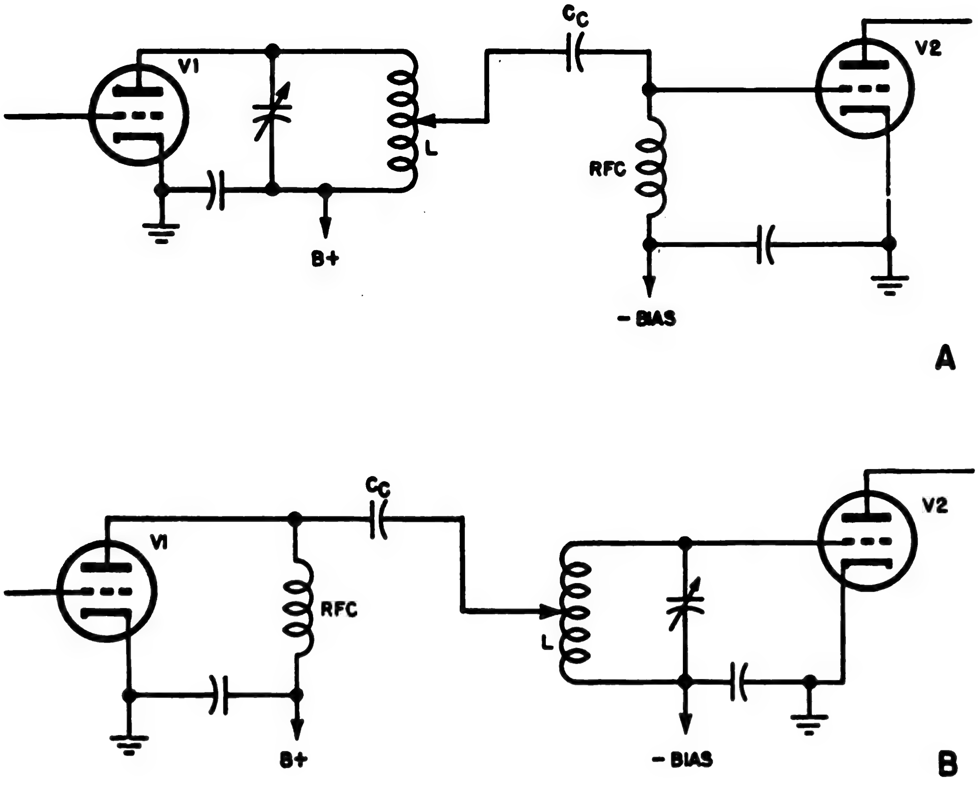

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Figure 73. Impedance-coupling circuits.

tions, the procedure is to wind the coils so that one turn of *L*2 is sandwiched between two turns of *L*1. In other circuits, *L*2 is insulated wire passed through the center of hollow copper tubing which is used for *L*1. In figure 76, the coils are wound in a unity-coupled r-f transformer. This method of interstage coupling rarely is used in military transmitters because of the mechanical difficulties encountered in adjusting the coupling to provide the proper excitation for the driven amplifier.

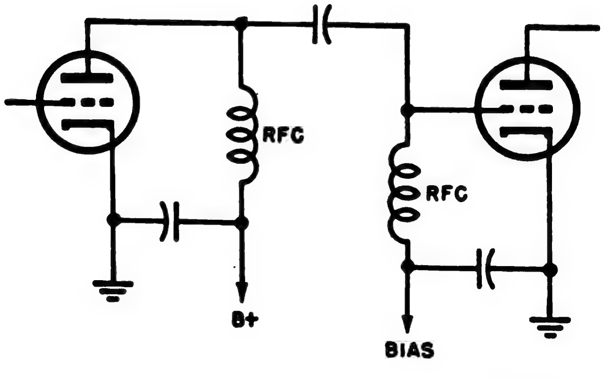

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Figure. 74. Untuned impedance coupling.

e. Link Coupling (fig. 77).

(1) Link coupling is a special form of inductive coupling. It requires the use of two tuned circuits, one in the plate circuit of the driver tube and the other in the grid circuit of the amplifier. A low impedance r-f transmission line having a coil of one or two turns at each end is used to couple the plate and grid tank circuits. The coupling links or loops are coupled to each tuned circuit at its cold end (point of zero r-f potential). Circuits which are cold near one end are called unbalanced circuits. Link coupling systems normally are used where the two stages to be coupled are separated by a considerable distance. One side of the link is grounded in cases where harmonic elimination is important or where capacitive coupling between stages must be eliminated.

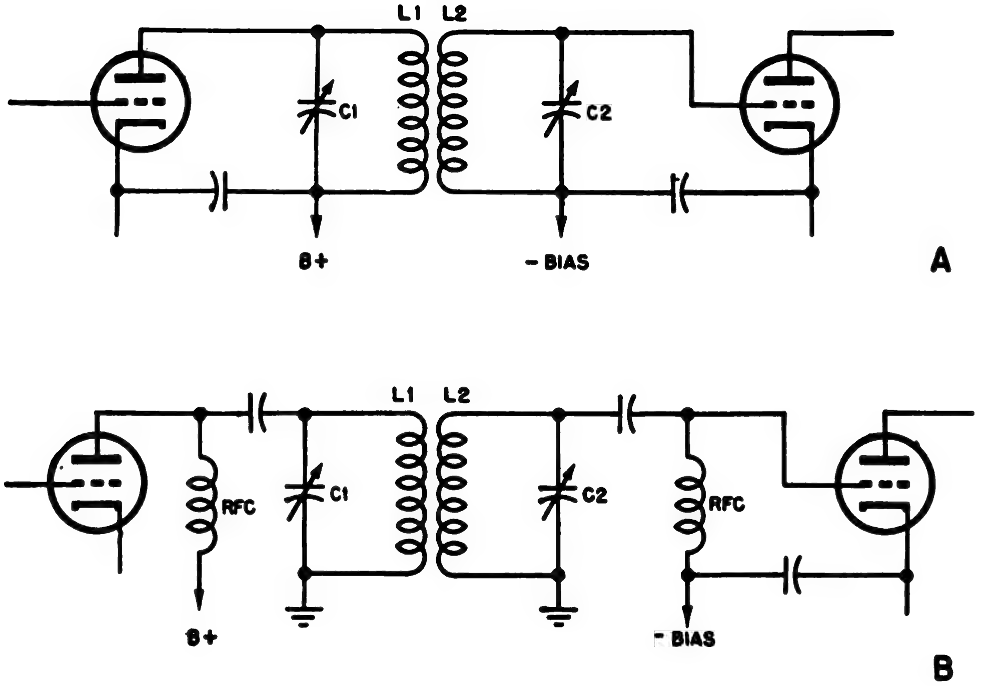

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Figure 75. Inductive interstage coupling.

(2) Some types of transmitter circuits require the use of a balanced circuit. This is one in which the d-c voltage is fed to the center of the tuned coil and equal r-f voltages are developed at the ends. In this way, neither end of the circuit is at r-f ground potential. Figure 78 shows how an unbalanced circuit is link-coupled to a balanced circuit.

(3) Link coupling is a very versatile interstage coupling system. It is used in transmitters when the equipment is sufficiently large to permit the coupled coils to be so positioned that there is no stray capacitive coupling between them. Link

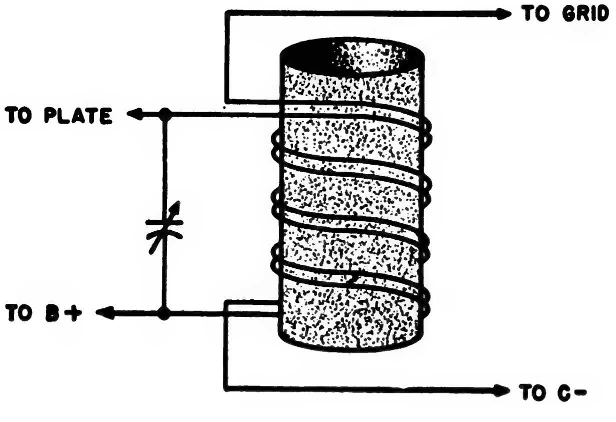

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Figure 76. Unity-coupled r-f transformer.

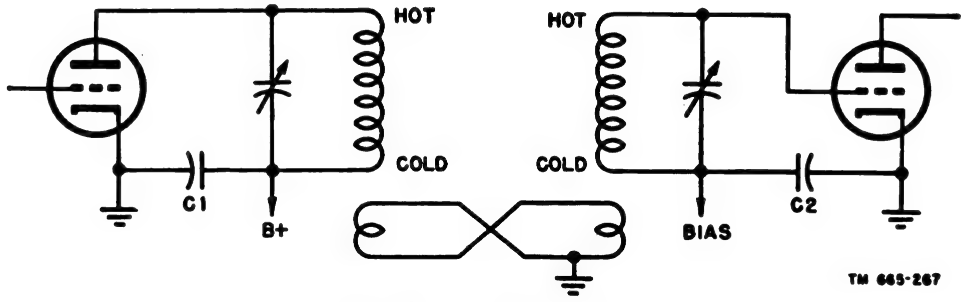

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Figure 77. Link coupling.

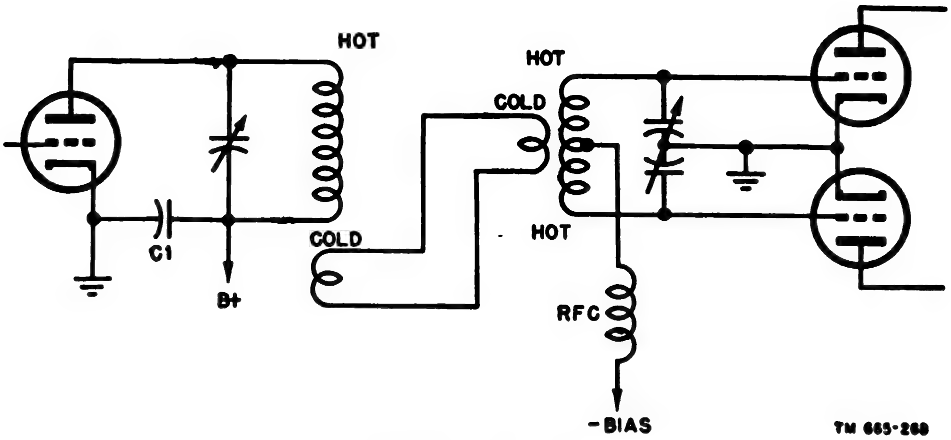

Figure 78. Balanced link coupling.

circuits are designed to have low impedance so that r-f power losses are low. Coupling between the links and their associated tuned circuits can be varied without complex mechanical problems. These adjustments provide a means of obtaining very low coupling between stages. The elimination of stray capacitive coupling makes neutralization easier and provides for reduction of harmonic transfer between stages.

58. Tuned Circuits Used for Coupling

a. Need for Tuned Circuits. The maximum amount of r-f energy is transferred from one stage to another when the interstage coupling system includes a tuned circuit which accepts r-f oscillations at the desired frequency and rejects r-f at all other frequencies. When a circuit accepts the desired frequency it is said to be tuned to resonance, and it is resonated by adjusting the capacitor or inductor.

b. Types of Tuned Circuits.

(1) There are two types of resonant circuits. The parallel tuned circuit has a high impedance at the resonant frequency, the line current is low, but the circulating tank current is high. The impedance of a series resonant circuit is minimum and equal to the circuit resistance at the resonant frequency. The reactance across the inductor and capacitor, individually, however, is large. Therefore the voltage developed across a reactance is higher than that developed across the entire circuit. The voltage drops across the reactances are found from the formulas

$$E_L = E \times \frac{X_L}{R}$$

$$E_C = E \times \frac{X_C}{R}$$

where E_L and E_C are the voltage drops across the inductor and capacitor, respectively, R is the circuit resistance, and E is the voltage delivered by the generator. Assume that the resistance of the inductor is 10 ohms, and that its reactance is 500 ohms at the resonant frequency. The generator develops 5 volts across the circuit resistance, R. The voltage across L is E times X_L/R, or 5 times 500/10, which equals 250 volts. Therefore, a series resonant circuit can be used to produce a voltage step-up.

(2) Sometimes it is difficult to determine whether a tuned circuit is a series or a parallel arrangement without a careful examination of the circuit. At first glance, tuned circuits Nos. 1 and 2 in figure 79 both appear to be parallel resonant. Circuit No. 1 is parallel resonant because it receives its voltage from the plate of the tube to which it is connected. Circuit No. 2, however, is series-resonant because of the method of applying the voltage to the circuit. Instead, the voltage is induced in *L*2 (the secondary of the r-f transformer) and is considered to be developed in series with the capacitor and inductor. In this transformer-coupled circuit, the maximum voltage is developed across

*L*1 at resonance because of the high impedance of circuit No. 1. The voltage in *L*1 induces a voltage in the secondary of the transformer. Since *L*2 is in a series-resonant circuit, the voltage on the grid of the tube will be greater than the induced voltage by the ratio of the reactance to the circuit resistance.

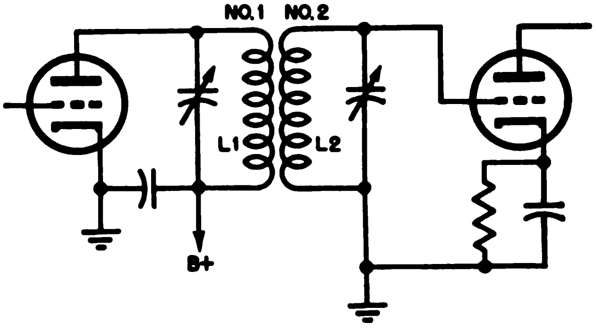

Figure 79. Transformer-coupled stages.

c. Tuning Procedure.

(1) Amplifier and oscillator circuits are tuned to the desired frequency by selecting the proper values of inductance and capacitance. The resonant frequency is continuously varied over a wide range by using a variable capacitor, a variable inductor, or a combination of both.

(2) Most tunable circuits are adjusted by using a variable capacitor in parallel or series with a suitable inductor. In modern transmitter and receiver circuits, it often is desirable to tune two or more circuits simultaneously. This usually is accomplished by using a capacitor having all rotorplate sections on a common shaft and the statorplate sections at the proper places along the stator frame. Each statorplate section is insulated from the others and from the frame. Such a capacitor is called a ganged capacitor and all circuits tuned by such a unit are said to be *ganged.*

(3) Some circuits are designed to be adjusted to one of a number of preset frequencies. Figure 80 shows an electron-coupled oscillator which is tuned to the desired frequencies by operating a switch. This circuit is adjusted to the highest desired frequency by adjusting *C*1 with the selector switch set in position 1. Lower frequencies are selected by rotating the selector switch to positions 2, 3, and 4. In positions above 1, a small variable capacitor is connected in parallel with *C*1. This increases the circuit capacitance and lowers the frequency.

(4) In some circuits, it is desirable for reasons of simplicity or design considerations to tune a circuit by varying the inductance rather than the capacitance. The most common method of varying inductance is to vary the position of a brass or powdered iron slug within the core of the coil (fig. 81). This method of tuning is called *slug tuning.* When a current is passed through the winding of an air core coil, there is a certain number of lines of magnetic force for each square inch of core area. If a core of magnetic material, powdered iron for example, is inserted in the coil, the number of magnetic lines of force will increase within the core considerably. This causes the effective inductance of the coil to increase. The increase varies directly as the permeability of the core. An increase in in-

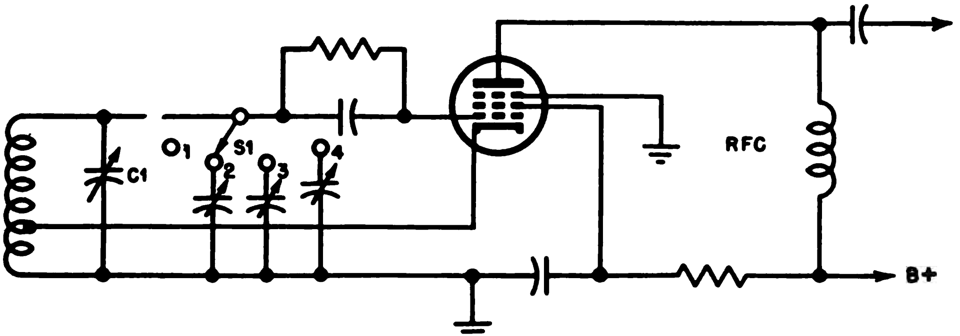

Figure 80. Electron-coupled oscillator with preset frequencies.

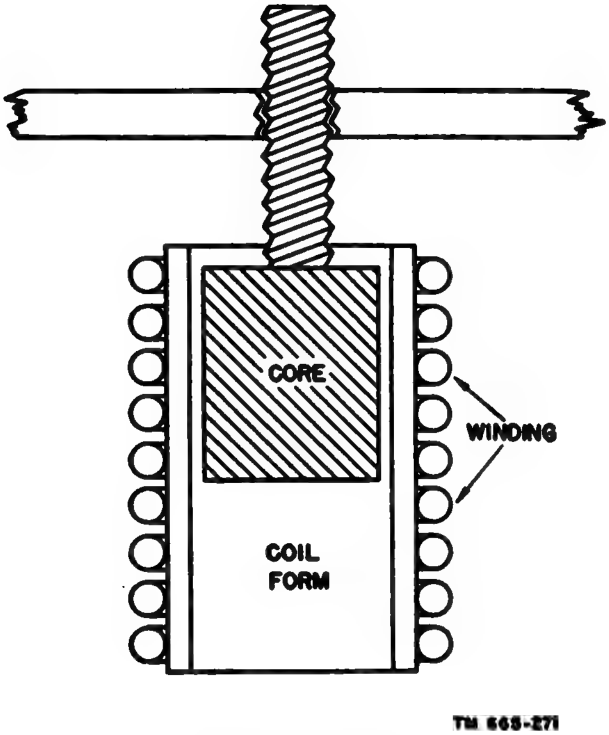

Figure 81. Slug-tuned coil.

ductance causes a decrease in the frequency of the tuned circuit.

(5) If the tuning slug is made of brass or other conductor, the opposite effect is obtained. Inserting the slug into the coil decreases the number of magnetic lines per given area and causes a decrease in the effective inductance. By mechanical means, the slug can be moved in and out of the coil form to produce the desired change in resonant frequency.

(6) Still another method of varying the inductance of a coil, often used when one coil is used for two or more tuning ranges, is to short circuit some of the turns. This may be accomplished by a switch connected to taps on the turns (A of fig. 82). Short-circuiting turns of a coil reduces the effective number of turns and decreases the inductance. For continuous variation of inductance, the coil may be wound in a single layer. A small roller is positioned so that it rides trolley fashion along the turns and effectively short circuits all turns between the roller and one end of the coil (B of fig. 82).

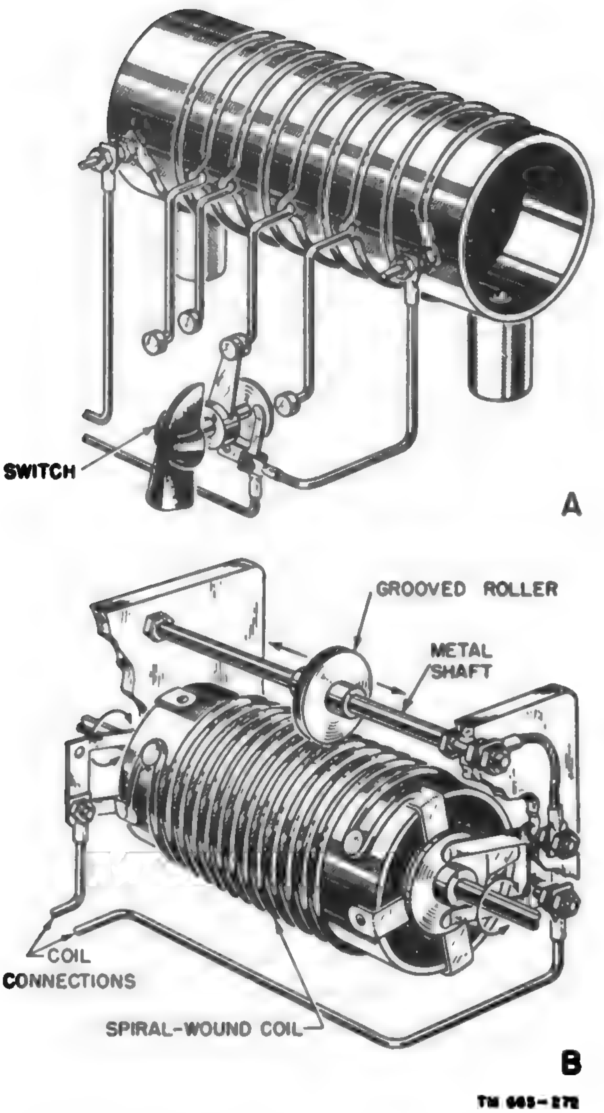

Figure 82. Methods of short-circuiting turns of an inductor.

59. Neutralization in R-f Amplifiers

a. Need for Neutralization.

(1) In the fundamental r-f amplifier shown in figure 83 the input signal is applied to the grid circuit and the power output is taken from the tuned plate circuit. Both input and output circuits are tuned to the signal frequency. This basic amplifier circuit resembles the tuned-plate tuned-grid oscillator. Therefore, the amplifier itself can function as an oscillator. The amplifier oscillates because of the feedback of energy from plate to grid through the plate-to-grid interelec-

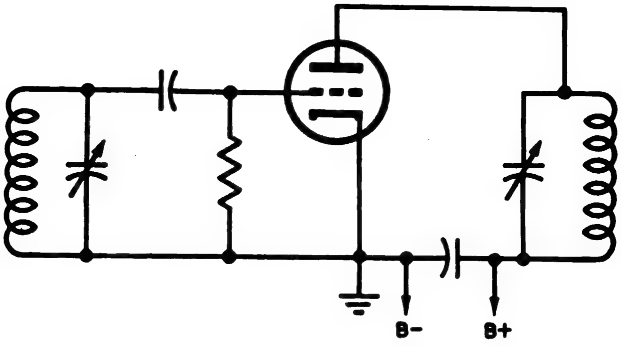

Figure 83. Triode r-f amplifier.

trode capacitance of the tube. This causes an unstable operating condition, distortion, spurious radiations, and interference to nearby radio receivers. Oscillation within the amplifier can be prevented by feeding back to the grid, through an external circuit, a voltage which is at all times equal but opposite in phase to the voltage fed back to the grid through the plate-to-grid capacitance. The voltage through the tube is canceled out by the voltage fed back through the external circuit. Since the feedback voltage through the tube is canceled, oscillation cannot take place. This process of preventing self-oscillation is called *neutralization.*

(2) Neutralization is necessary in triode amplifiers operating at approximately 500 kc or higher. Neutralization seldom is necessary in an amplifier using pentodes or beam power tubes which have a very small plate-to-grid capacitance. Transmitting-type tetrodes and pentodes are designed to operate without neutralization when simplicity is important.

b. Neutralization Systems. There are several well-known neutralization systems. Two of these, the plate or Hazeltine neutralization system, and the grid or Rice system, have the advantage or being useful over a wide frequency range. Radio-frequency amplifiers having a single tube or group of parallel tubes may use either a balanced tuned-plate or a balanced tuned-grid circuit to supply the feedback voltage in proper phase to prevent oscillation. Circuits in which out-of-phase voltages are fed back to the grid are *degenerative* and tend to decrease any change in voltages applied to the grid.

(1) *Plate neutralization* (fig. 84). Plate, or Hazeltine neutralization results when the degenerative feedback is obtained by means of a tapped plate coil. The circuits shown in A and B are suitable for use in c-w transmitters operating below approximately 6 mc. Above this frequency, minor unbalances in the inductive portion of the circuit may cause regeneration and the amplifier may be unstable. For amplifiers at higher fre-

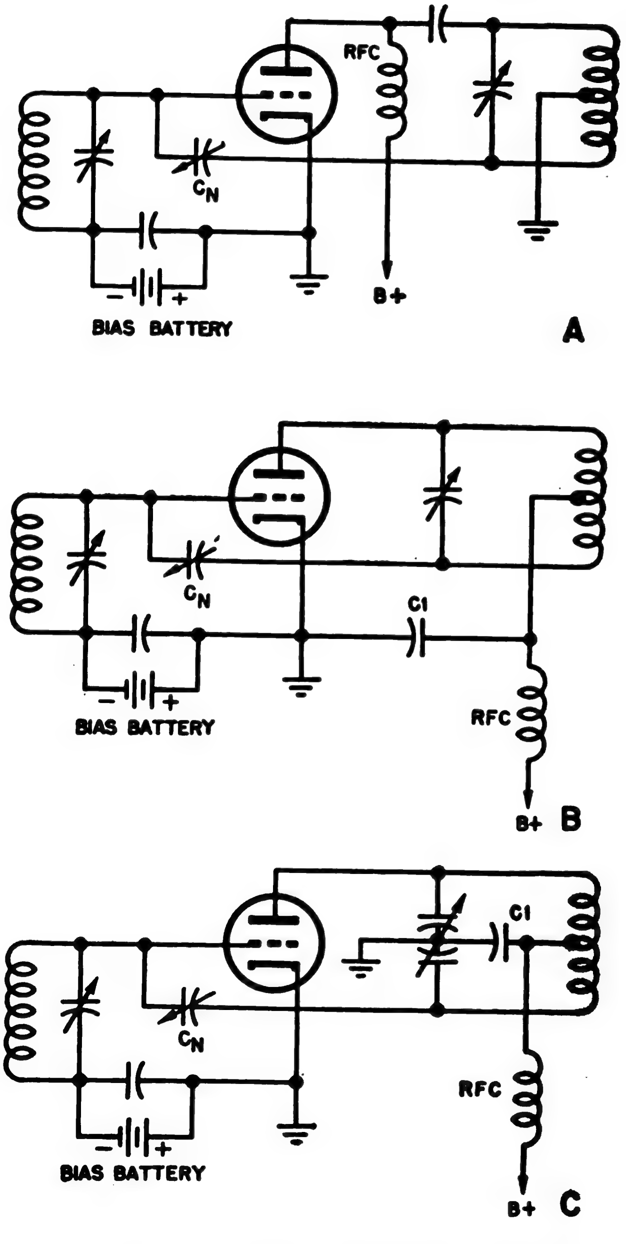

Figure 84. Plate neutralization.

quencies, the circuit in C, having a split stator capacitor, is used. This makes the circuit balanced and the division of voltage independent of mutual coupling between the halves of the coil. If the neutralization adjustment is made at the highest frequency, it will be sufficiently close to provide satisfactory operation at lower frequencies.

(2) *Grid neutralization* (fig. 85). In the grid, or Rice neutralization system, the tapped coil is in the grid circuit. A voltage is fed back through neutralizing capacitor C_N to the lower end of the tapped grid coil. The polarity of this voltage is reversed at the grid end of this coil. As a result, the feedback voltage is 180° out of phase with the voltage applied to the grid through the plate-to-grid capacitance. When the neutralizing capacitor is adjusted properly, the degenerative feedback through C_N just balances the voltage that is fed back through the tube, and proper neutralization occurs.

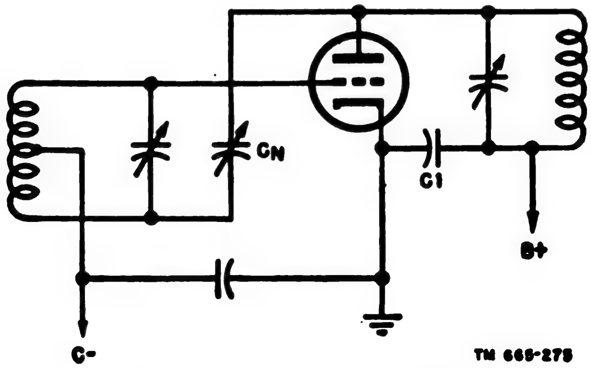

Figure 85. Grid neutralization.

(3) *Relative merits.* Plate neutralization has an advantage over grid neutralization in that one-half as much grid drive is required, but also the disadvantage that the plate tank capacitor must be rated at twice the B-plus voltage. Conversely, grid neutralization is advantageous because the tank capacitor may be rated at the value of the B-plus voltage, and disadvantageous because twice as much grid drive is required as compared with the plate system.

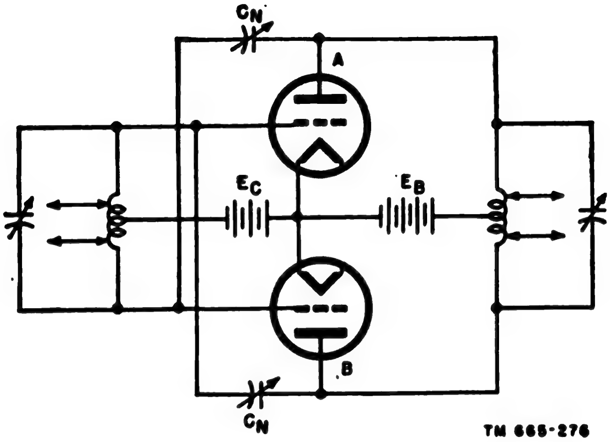

Figure 86. Cross neutralization.

(4) *Cross neutralization* (fig. 86). This type of neutralization is used in push-pull circuits. The plate voltage of tube *A* is normally 180° out of phase with the plate voltage of tube *B*. Therefore, the neutralization can be accomplished quite simply. A portion of the output voltage of tube *A* is applied through a neutralizing capacitor to the grid of tube *B*. A portion of the output voltage of tube *B* is applied through a second neutralizing capacitor to the grid of tube *A*. When the neutralizing capacitors are adjusted properly, correct neutralization occurs.

(5) *Link neutralization* (fig. 87). This system sometimes is used to stabilize pentode and tetrode amplifiers which are on the verge of oscillation because of insufficient shielding between grid and plate circuits or stray exterior coupling between input and output circuits. The feedback volt-

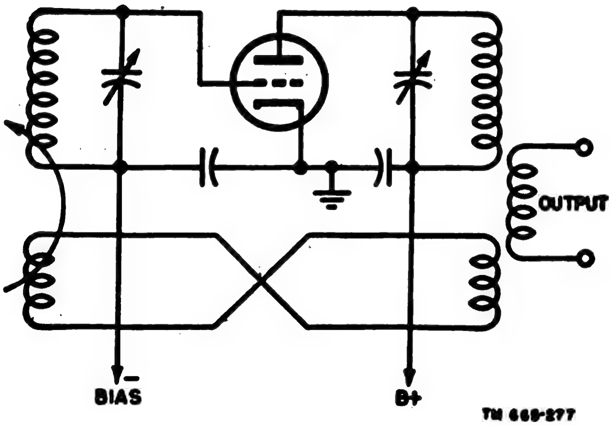

Figure 87. Link neutralization.

age is taken from the cold end of the plate coil and applied to the cold end of the grid coil through a link coupling circuit similar to that used for interstage coupling. The proper phase relationship is obtained by reversing the connections to one of the feedback loops. The voltage fed back through the link is balanced with that fed back through the tube by varying the coupling between one of the loops and the tank circuit to which it is coupled.

(6) *Inductive neutralization* (fig. 88). Inductive or shunt neutralization differs from the systems previously described. In other circuits, the voltage fed back through the plate-to-grid capacitance is canceled by an equal but opposite voltage fed back through an external path. In this circuit, we can nullify the effect of the plate-to-grid capacitance by paralleling it with an inductor having the same value of reactance. Since the two reactances are equal and opposite, we have a parallel resonant circuit between the grid and the plate. Since a parallel resonant circuit offers a very high impedance at its resonant frequency, there is no transfer of energy through the circuit from plate to grid. $C1$ is a blocking capacitor which prevents the flow of direct current. This circuit has the advantage that it can be used only for neutralization at a single frequency of operation only.

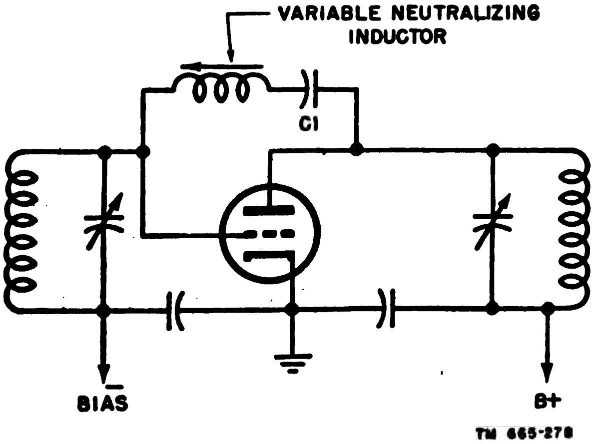

Figure 88. Inductive neutralization.

c. *How Circuits are Neutralized.*

(1) Several techniques can be used in neutralizing r-f amplifiers. The most common of these is performed with the plate voltage removed from the stage being neutralized. Radio-frequency excitation is applied to the grid circuit. An r-f indicator (such as a neon lamp or a dial lamp connected to the ends of a single-turn loop of wire) is coupled to the plate tank circuit. If the stage is not neutralized, the indicator glows when the plate tank is tuned to resonance with the grid circuit. The neutralizing capacitor or other neutralizing adjustment should be varied slowly until all indication of r-f disappears from the plate tank. The grid and plate circuits should be retuned after each adjustment of the neutralizing control. Push-pull amplifiers are adjusted in the same manner. The adjustment is carried out more quickly if the neutralizing capacitors are first adjusted to approximately the same capacitance. These capacitors should remain at approximately the same capacitance throughout the neutralizing procedure.

(2) A commonly used indicator is a low range d-c millimeter in the grid circuit of the stage to be neutralized. Some transmitters have amplifier grid current meters; others have provisions for switching a meter into the grid circuit. First, disconnect the plate voltage. Next, apply sufficient excitation to produce an indication on the meter, and then tune the grid circuit to resonance as indicated by maximum grid current. If the stage is not neutralized, the d-c grid current varies as the *plate tank capacitor* is tuned through resonance. The neutralizing capacitor or other neutralizing adjustment should be varied slowly until there is no change in d-c grid current as the plate tank capacitor is tuned through resonance.

(3) If the stage being neutralized is not the final amplifier, a slightly different technique can be used. A d-c grid current meter is inserted in the grid circuit of the stage following the buffer or intermediate amplifier being neutralized. The plate

voltage then is removed from the stage being neutralized and from all stages following it. The stage being neutralized is tuned to resonance, and the following stage is resonated. A small amount of grid current will be observed as long as the stage is not fully neutralized. The neutralizing adjustment is varied until there is no indication of grid current in the following stage.

60. Frequency Multiplication

a. Frequency multipliers are special class C amplifiers operated with three to ten times cut-off bias and used to generate a frequency that is a multiple of a lower frequency. Such multiple frequencies are called harmonics, and circuits designed to develop harmonic frenquencies are called harmonic generators or frequency multipliers. The signal fed to a frequency multiplier is the fundamental or first harmonic. The second harmonic is twice the fundamental, the third harmonic is three times the fundamental, and so on.

b. Frequency multipliers operate by virtue of pulses of plate current produced by a class C amplifier. The plate-current pulse usually is quite distorted. As such, it contains harmonics of the fundamental operating frequency. Although the plate current flows in pulses, the alternating plate voltage is sinusoidal because of the filter or flywheel action of the tank circuit. When the output tank circuit is tuned to the required harmonic frequency, the tank acts like a filter, accepts the desired harmonic and rejects all other harmonics, and frequency multiplication results.

c. The harmonic content and efficiency of a frequency multiplier increase as the angle of plate current flow is decreased. To reduce the angle of flow, higher grid bias is used so that the excitation voltage exceeds the cut-off voltage for a shorter period of time. The chart below shows the plate-current pulse length and power output of harmonic generators.

Harmonic	Optimum length of plate-current pulse in electrical degrees at the fundamental frequency	Percentage of output from class C first-harmonic amplifier
2	90 to 120	65
3	80 to 102	40
4	70 to 90	30
5	60 to 72	25

d. In the circuit of a typical frequency multiplier in A of figure 89, the plate tank circuit is tuned to the second harmonic. This circuit is referred to as a doubler. A tripler is a frequency multiplier whose output tank circuit is tuned to the third harmonic. A quadrupler produces an output frequency which is four times the fundamental frequency. Frequency multipliers seldom operate above the fifth harmonic because of their greatly reduced output power. Frequency multipliers need not be neutralized because the plate tank circuit is not tuned to the same frequency as the grid tank circuit.

e. Two tubes can be connected with their plates in parallel and their grids in push-pull as in B. With the grids thus fed out of phase, one pulse is produced in the common plate circuit for each half cycle of excitation. This circuit is called a push-push doubler. Not only is the excitation frequency doubled, but the circuit has the added advantage of balancing out the fundamental and all odd hormanics. A push-push doubler delivers more power output than the same two tubes operated in parallel as a doubler, using the circuit arrangement shown in A. The push-push circuit is useful also as a quadrupler when the output tank circuit is tuned to four times the input frequency.

61. Grid Biasing

Bias is used on the grid of an electron tube amplifier to insure that it operates on the proper point of the plate-current grid voltage curve. There are a number of methods of supplying the required negative biasing voltage.

a. Fixed bias is obtained from batteries (fig. 89) or from a rectifier power supply. An electron tube can be connected so that it supplies all or part of its own operating bias. Such circuits are called *self-biasing* circuits.

b. One method of self-biasing is to insert a resistor between the cathode and ground of the electron tube amplifier (fig. 90). This method is called cathode resistor bias, or simply cathode bias. Current drawn by the plate and grid (and screen grid in tetrodes and pentodes) flows through resistor *R*1 in a direction which makes the cathode end positive in respect to the lower end (ground). Omitting *R*2 for the moment, the grid of the triode is grounded through the grid tank circuit. Since bias is the voltage difference between the grid and the cathode, making the cath-

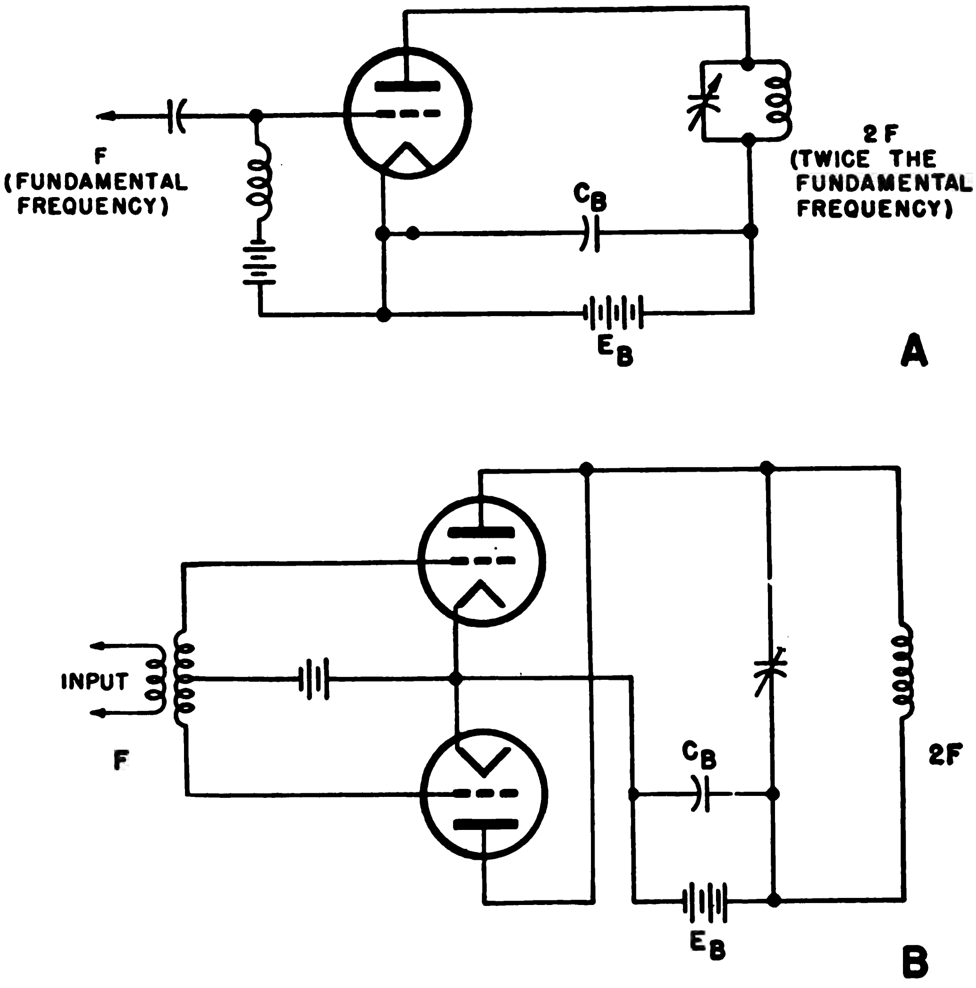

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Figure 89. Frequency-doubler circuits.

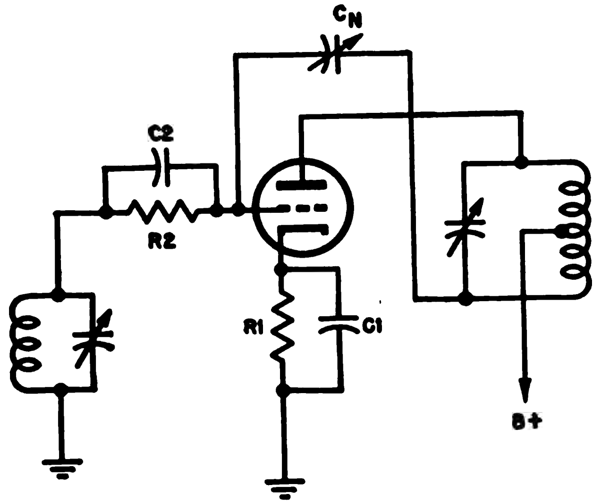

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Figure 90. Cathode bias and grid-leak bias in an amplifier.

ode positive in respect to the grid is equivalent to making the grid negative in respect to the cathode. Bias developed in this manner is called automatic bias. The value of the biasing resistor is chosen so that the sum of the currents flowing in the cathode circuit biases the tube for proper operation.

c. An increase in excitation causes the total cathode current to increase. The rise in cathode current causes an increased drop across resistor *R*1. This tends to hold the cathode current constant by making the grid more negative and so partially canceling the effect of increased excitation. Capacitor *C*1 presents a low reactance at the excitation frequency so that a-c pulsations in the plate circuit do not affect the operating bias. It is not feasible to use cathode bias to develop the large negative bias necessary to bias the tube below the bend in the E_g–I_p curve, because plate current must flow in order for bias to be developed. For this reason, cathode bias is used more extensively in class A amplifiers which are biased above cut-off. Cathode bias in class C r-f amplifiers generally is used in combination with fixed bias or grid-leak bias.

d. A resistor can be connected in the grid circuit of an r-f amplifier to provide grid-leak bias. Resistor *R*2 in figure 90 is of the d-c grid return path. R-f excitation, applied to the grid of the tube causes the grid to go positive and draw grid current on the peaks of the excitation cycle. This current flows through the grid-leak resistor and produces a voltage drop. The direction of grid-current flow is such that the grid is biased negatively in respect to the cathode. Capacitor *C*2 across *R*2 bypasses any r-f energy that may be present. The value of *R*2 is selected so that the voltage drop across it develops the required amount of bias.

e. The bias voltage is the product of the grid current in amperes and the grid-leak resistance in ohms. Grid-leak bias automatically adjusts itself for fairly wide variations in excitation. Its advantage lies in the fact that very high biasing voltages can be developed without using separate voltage sources. Its main disadvantage is that the bias developed across the resistor is lost when excitation fails. To protect the tube against excessive currents when excitation is interrupted, grid-leak and cathode bias often are used in combination. The cathode bias is used to limit the flow of plate current to a safe value when the preceding stage is keyed or when excitation fails.

62. Keying

a. The carrier of a c-w transmitter is broken into short and long pulses (dots and dashes) of r-f waves in accordance with the characters of the international Morse code. A radiotelegraph key like that shown in figure 91 is used to control the output of the transmitter. When the key is closed, the transmitter radiates the r-f signal. No signal is radiated as long as the key is open.

b. In general, the keying of a transmitter is considered satisfactory if the r-f output is zero when the key is open and maximum when the key is closed. If the output does not drop to zero under key-up conditions, the signal is said to have a *backwave.* A strong backwave may reach a distant receiver and make the keying difficult to read. The effect is as though the dots and dashes were simply louder portions of a continuous carrier. In code transmissions, there are intervals between dots and dashes and between letters and words. No r-f is radiated during these brief intervals. If the receiver operates with normal sensitivity during these intervals, it is possible for the receiving operator to signal the transmitting operator by holding his key down. In this way, the receiving operator can signal the transmitting operator immediately when he has not been able to copy a part of the message because of fading, static, or interference. The ability of an operator to hear signals during key up intervals is called *break-in operation.* The oscillator may run continuously for break-in if it is inaudible in the receiver at the transmitting station.

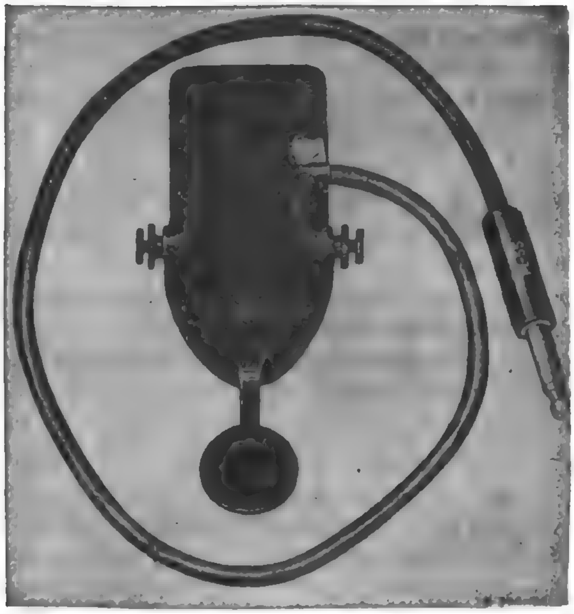

Figure 91. Radiotelegraph key.

c. Another requirement of satisfactory keying is that is should take place smoothly without key clicks which cause interference to stations receiving on other frequencies. Key clicks are caused when the output of the transmitter is changed too abruptly, and under these conditions side bands are produced. The oscillator should be absolutely stable while it is keyed. If it is not, the frequency shifts and causes a varying note (chirp) which makes the signal difficult to copy.

d. To avoid backwaves, the oscillator stage frequently is keyed directly. On the other hand, it is easier to avoid chirps by keying the transmitter in a stage between the oscillator and antenna. Since any chirp resulting from frequency shift is multiplied in each frequency multiplier, it is difficult to produce chirpless keying in a keyed oscillator operated at a frequency several times lower than the output frequency. When keying takes place in a stage other than the oscillator, the oscillator is on all the time. It must operate at very low power and must be well shielded and isolated to prevent radiation of a backwave (from the oscillator). If the oscillator does not meet these conditions, the backwave may be radiated even though the stages between the oscillator and the antenna are cut off. Energy from the oscillator may leak to the antenna through improperly neutralized amplifiers or capacitive and/or inductive coupling between the oscillator and antenna circuits.

63. Keying Circuits

A number of methods may be used for keying a transmitter. Most of them can be applied to the oscillator or amplifier stages. A transmitter can be keyed by opening and closing, simultaneously, the plate circuits of all the stages. The oscillator alone, or a stage between the oscillator and the final amplifier can be keyed. This is called *excitation keying* because excitation is applied to and removed from the input of the final amplifier while its plate voltage is applied.

a. Center-Tap or Cathode Keying. If the stage to be keyed has a directly heated cathode operated from an a-c source, the key can be inserted between the center tap on the filament transformer and the B-minus lead (fig. 92). The key opens and closes the negative side of the plate circuit. No plate current flows when the key is open. With indirectly heated tubes, the key is inserted between the cathode and the B-minus lead.

b. Simple Blocked Grid Keying. An amplifier or oscillator can be keyed by applying sufficient negative bias to the control grid to cut off the flow of plate current when the key is up. This blocking bias must be considerably higher than the normal cut-off grid bias because it must overcome the excitation voltage. It is removed by closing the key. The circuit in A of figure 93 uses cathode bias along with grid-leak bias. The addition of the cathode bias reduces the plate current and resultant output considerably. When the key is open, plate current through resistor *R* causes a voltage drop which makes the end of *R* connected to R_G negative in respect to the cathode end. If *R* is sufficiently large, the voltage drop is sufficient to reduce the plate current almost to cut-off. Closing the key short-circuits resistor R, removing the cathode bias and permitting normal plate current to flow. Resistor R_G is the usual grid-leak resistor which develops normal operating bias. Total plate-current cut-off is not possible with this system.

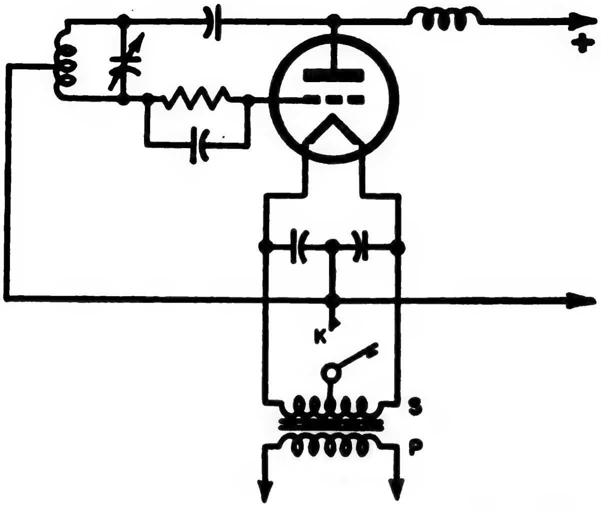

Figure 92. Center-tap or cathode keying.

c. Zero-Current Blocked Grid Keying. The circuit arrangement shown in B affords full plate-current cut-off when the key is opened. The cathode of the tube is connected to a tap on a voltage divider. When the key is open, the full 1,000 volts appears across the 100,000-ohm and the 200,000-ohm resistors in series. Since the voltage divides in direct proportion to the resistances, two-thirds (667 volts) of the supply voltage appears across the 200,000-ohm resister between the plate and cathode and 333 volts appears across the 100,000-ohm resistor between the grid and cathode. When the key is open, the 333 volts adds to the 100 volts of fixed bias. This high negative bias cuts off the tube completely. When the key is closed, the 100,000-ohm resistor is shorted out and the full 1,000 volts appears between the plate and cathode. The grid bias is reduced to 100 volts, and the amplifier operates normally.

d. Screen Grid Keying. In some transmitters, the key is inserted in series with the screen grid of the amplifier or oscillator tube. If the key is

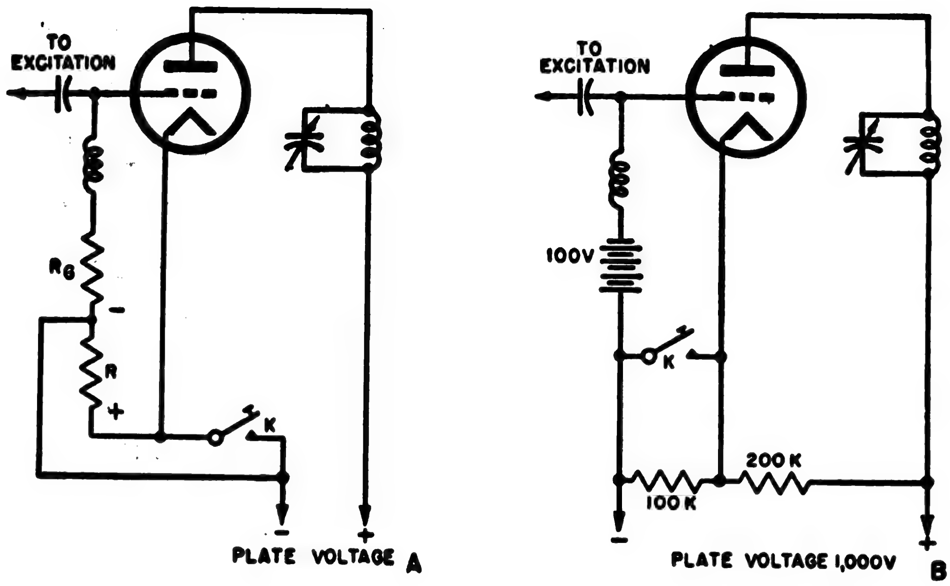

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Figure 93. Blocked grid keying.

inserted in the screen grid circuit of an electron-coupled oscillator, it effectively breaks the *plate* circuit of the triode oscillating circuit and no r-f current will be developed. To prevent chirps, the voltage at the screen grid is regulated.

e. Keying Portable Sets. Most portable and mobile sets used in the field operate from batteries r from hand-driven generators. Under such conditions, it is desirable that the transmitter load on the power supply be kept as low as possible. For this reason, the transmitting key often is inserted at a point in the circuit where it opens and closes the plate circuits of all tubes in the transmitter, thus removing the entire load from the power supply when the key is open.

f. Electron Tube Keying.

(1) Large fixed station transmitters often have their output keyed at speeds of several hundred words per minute. Most of these transmitters incorporate special *keying tube* circuits. The keying tube usually is connected to a point in the circuit where the presence or absence of plate-current flow affects critical operating voltages in one or more of the stages in the transmitter and causes the transmitter to be turned on and off.

(2) A typical electron tube keying circuit consists of a triode tube connected between the cathode and ground of the r-f amplifier or oscillator to be keyed. This tube, called a *keyer* tube, operates with its grid biased to cut-off when the key is open. Since this tube is cut off, it acts as an infinitely high resistance (open circuit) between the cathode and ground of the amplifier stage. The amplifier cannot conduct as long as the keyer tube is cut off. Closing the key removes the bias so that the keyer tube becomes highly conductive. This enables normal plate current to flow in the amplifier stage. Generally, zero current blocked grid keying is used on the keyer tube to insure that it and the keyed stage are cut off completely.

(3) Elaborate circuits based on these electron tube keying systems are used on some large fixed station transmitters, particularly when the transmitter is operated from a remote point. In some cases, the biasing voltage for the keyer tube grid is sent over wire circuits to the transmitter which may be at some remote point. In such circuits, the control wires can be considered as simply extensions of the keying leads. Some remote control systems use standard telephone circuits. As an example, the output of a keyed audio oscillator can be fed into standard telephone lines at the operating point. The audio tone passes through

the telephone circuits to a receiver at the transmitter location. The tone is taken off the phone wires, amplified, and then rectified to produce the voltage necessary to control the grid of the keyer tube.

g. Primary Keying. A simple method of providing clickless keying of an a-c operated transmitter is to insert the key in series with the primary of the power transformer supplying voltages to one or more of the stages. The normal power supply filter capacitor and inductance arrangement prevents the r-f signal from building up or falling off too rapidly. It is the rapid start and stop that causes clicks. If the building up and falling off occurs at too great a rate, high keying speeds cannot be used. This is true since the code characters tend to run together with indistinct separations.

h. Keying Relay. When a transmitter is keyed in a cathode or plate circuit, high voltages sometimes exist across the key contacts or between one side of the key and ground or chassis when the key is open. A slip of the hand on the transmitting key could result in a serious shock. Furthermore, an ordinary hand key cannot handle heavy currents without arcing. For these reasons, a keying relay is used sometimes in conjunction with a low voltage source to open and close the keyed circuit (fig. 94). The hand key, *K*, is placed in some position convenient to the operator. Closing the key completes the low voltage circuit through the battery and the coil *L* of the keying relay. The current through the coil magnetizes the core and the metal armature, *A*, is attracted to it, closing contact *C*. This contact is in series with the keyed circuit of the transmitter. Spring *S* opens the contacts when the key is opened by restoring the armature to its original position.

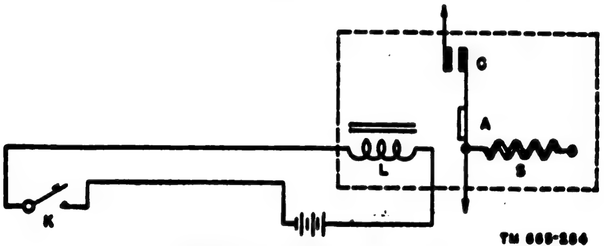

Figure 94. Keying relay.

i. Key Click Filters.

(1) Keying should produce clean cut dots and dashes which cause a minimum of interference in nearby receivers. However, keying does not instantaneously start and stop radiation of the carrier. The sudden application and removal of power causes large surges of current which result in unwanted oscillations and interference in the form of clicks which can be heard over a wide frequency range.

(2) To prevent such interference, key click filters are used in the keying systems of most transmitters. Two types of filters are shown in figure 95. The r-f chokes and bypass capacitors, in A, isolate the key from the rest of the circuit and bypass and prevent surges of r-f caused by arcing at the key contacts. A lag-circuit keying filter is shown in *B*. The inductor, *L*, causes a slight lag in the current as the key is closed. The current then builds up gradually instead of rapidly. Capacitor *C* releases its energy slowly when the key is opened. Resistor *R* controls the rate of charge and discharge of *C* when the key is opened and closed.

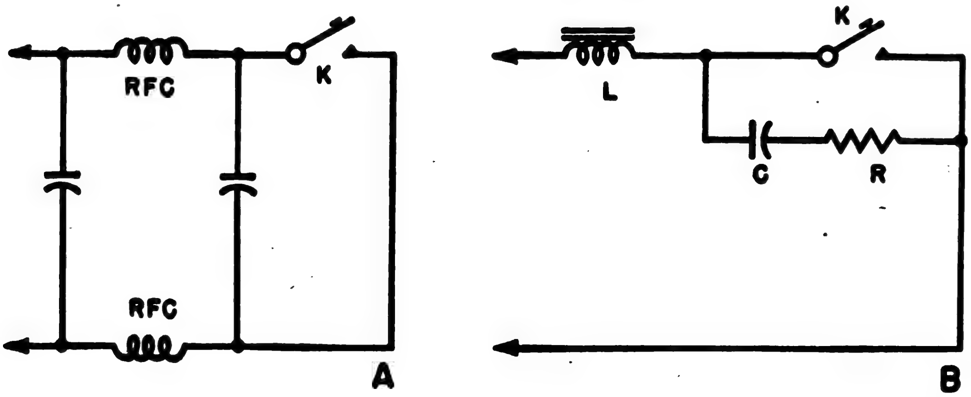

Figure 95. Key click filters.

64. Parasitics and Harmonics

a. Parasitic Suppression.

(1) Parasitic oscillations are oscillations at some frequency usually far removed from the frequency to which the transmitter is tuned. Any inductor will resonate at some frequency when associated with a capacitance. Occasionally, various transmitter components which possess both inductive and capacitive properties will cause the circuit to oscillate at their common resonant frequency. The inductance may be that of wiring, leads of capacitors, a section of a coil or r-f choke, or the element leads within a tube. The capacitance may be that of normal circuit capacitors, or the capacitance between turns of a coil or choke, or the interelectrode capacitance of the tube. Parasitics usually are eliminated in the design of the transmitter but they sometimes appear after the set has been modified or if some parts are replaced. Defective tubes are another cause of parasitics. The presence of parasitic oscillations is indicated by a rough, nonmusical note in the receiver and an indication of plate and grid current in a properly neutralized amplifier when excitation is removed. Parasitics reduce the useful power output of the transmitter by absorbing some of the power which should be useful output. They may cause excessive currents that blow fuses, trip overload relays, ruin capacitors and inductors in the oscillating circuit, and damage the tubes.

(2) High-frequency parasitics usually can be removed by inserting small r-f chokes or resistors in series with each grid and plate connection. These should be placed as close as possible to the tube terminals. Chokes for parasitic suppression have very low inductance and negligible distributed capacitance. The resistor can be approximately 50 ohms. An efficient parasitic suppressor can be made by winding a coil of wire on the body of a small carbon resistor and connecting the coil and resistor in parallel. This combination usually is most effective in grid circuits but its use may be necessary in some plate circuits. The presence of the parasitic suppressor in grid circuits makes the amplifier harder to drive at high frequencies but the decrease in the power sensitivity is compensated for by the lack of spurious oscilaltions. Low-frequency parasitics occur most often in amplifiers having r-f chokes in both grid and plate circuits. Sometimes the tube or tuning capacitor may be tapped down on a tank coil to provide proper impedance matching and to insure maximum energy transfer at the desired frequency.

b. Suppression of Harmonics.

(1) Harmonic radiation is particularly undesirable in a transmitter. It can cause severe interference to other stations authorized to operate on the harmonic frequencies. Furthermore, the generation of harmonics produces a definite power loss at the assigned frequency.

(2) Suppression or elimination of harmonic radiation can be accomplished in a number of ways. Some devices for the purpose are built into the transmitter and are beyond the control of the operator. He can do much to suppress harmonics, however, merely by tuning the transmitter properly and adjusting the operating voltages to the correct values. The harmonic content of an amplifier output increases as the bias and excitation voltages are increased. Therefore, by keeping the bias and excitation within specified limits, harmonic radiation is minimized.

(3) When r-f energy is transferred from one circuit to another by an inductive arrangement such as an r-f transformer or link coupling, the inductors have a certain amount of stray capacitance. The capacitance between the coils is small but far from negligible. Energy at the resonant frequency is transferred through magnetic coupling alone. However, harmonics are transferred between the inductors by electrostatic coupling through the capacitance. Therefore, if harmonics are to be eliminated, the coupling must be purely magnetic, and the capacitive effects must be excluded by inserting a Faraday shield between the two inductors (fig. 96). The Faraday shield (sometimes

called an electrostatic shield) consists of a group of parallel conductors, connected at one end only. This forms an effective shield against electrostatic coupling without affecting the transfer of energy through magnetic coupling.

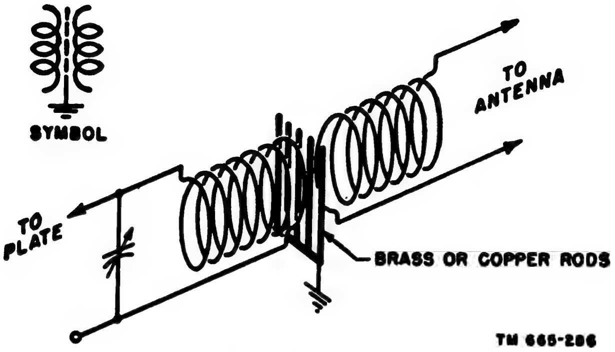

Figure 96. Faraday shield.

(4) An important factor in reducing harmonic radiation from high-frequency transmitters is the use of low-power frequency multipliers. When multiplication is at low power levels, direct radiation from the circuits involved is minimized and there is less danger of the multiplier signals and their harmonics leaking through to the antenna where they may be radiated. For this reason high-frequency transmitters often use receiving tubes as frequency multipliers. After the oscillator frequency is multiplied to the required output frequency, it is amplified to the required power levels by class C amplifiers biased only slightly beyond cut-off and supplied with the minimum of excitation required to develop sufficient power for driving the following stage. By operating the class C amplifiers with a large angle of plate-current flow, harmonic generation is minimized.

(5) Some transmitters have small auxiliary parallel tuned circuits in series with the plate lead and in series with each power line going to the power transformer. These circuits are tuned to the transmitter harmonics. They present a high impedance to the flow of harmonic currents. The tuned circuits in series with the power lines prevent harmonics from being radiated from the power lines. Radiation of harmonics can be reduced also by using an antenna which does not respond to harmonic frequencies. Special antenna coupling networks can be used to eliminate harmonics.

65. Antenna Coupling

a. Need for Antenna Coupling Networks. The primary purpose of antenna tuners or couplers is to provide the maximum transfer of power from the transmitter to the antenna. Most military transmitters are designed to operate over a wide range of frequencies under varying conditions. For example, one transmitter may be used with a whip antenna on tanks and similar land vehicles, with a long wire elevated antenna for fixed station use and another type of antenna when used in aircraft. Even in fixed station service, the type of antenna used depends on the operating frequencies and on the available space. An antenna tuning unit provides a means of reasonating any antenna that can be used and of varying the antenna-to-transmitter impedance match and coupling.

b. Antenna Coupling Circuits.

(1) The versatile antenna tuning unit shown in A of figure 97 is designed to connect a 2- to 18-mc transmitter to a whip antenna or to a long wire antenna. The circuit is shown in B when the antenna range switch is in position 1. In this position, a whip antenna is used and the frequency range covered is from 2 to 10 mc. Because the whip antenna is less than a quarter-wavelength long it presents a capacitive reactance to the transmitter, which is balanced out by the addition of a portion of inductor $L2$, the low-frequency loading coil. This inductor is varied by a movable tap which short circuits some of the turns. When the inductive reactance of $L2$ is equal to the capacitive reactance of the antenna, the load presented to the transmitter is purely resistance. Coupling coil $L1$ is link coupled to the power amplifier tank circuit. It acts in such a way that the resistance of the antenna is reflected back as an optimum load on the amplifier tank circuit. The antenna current meter is at

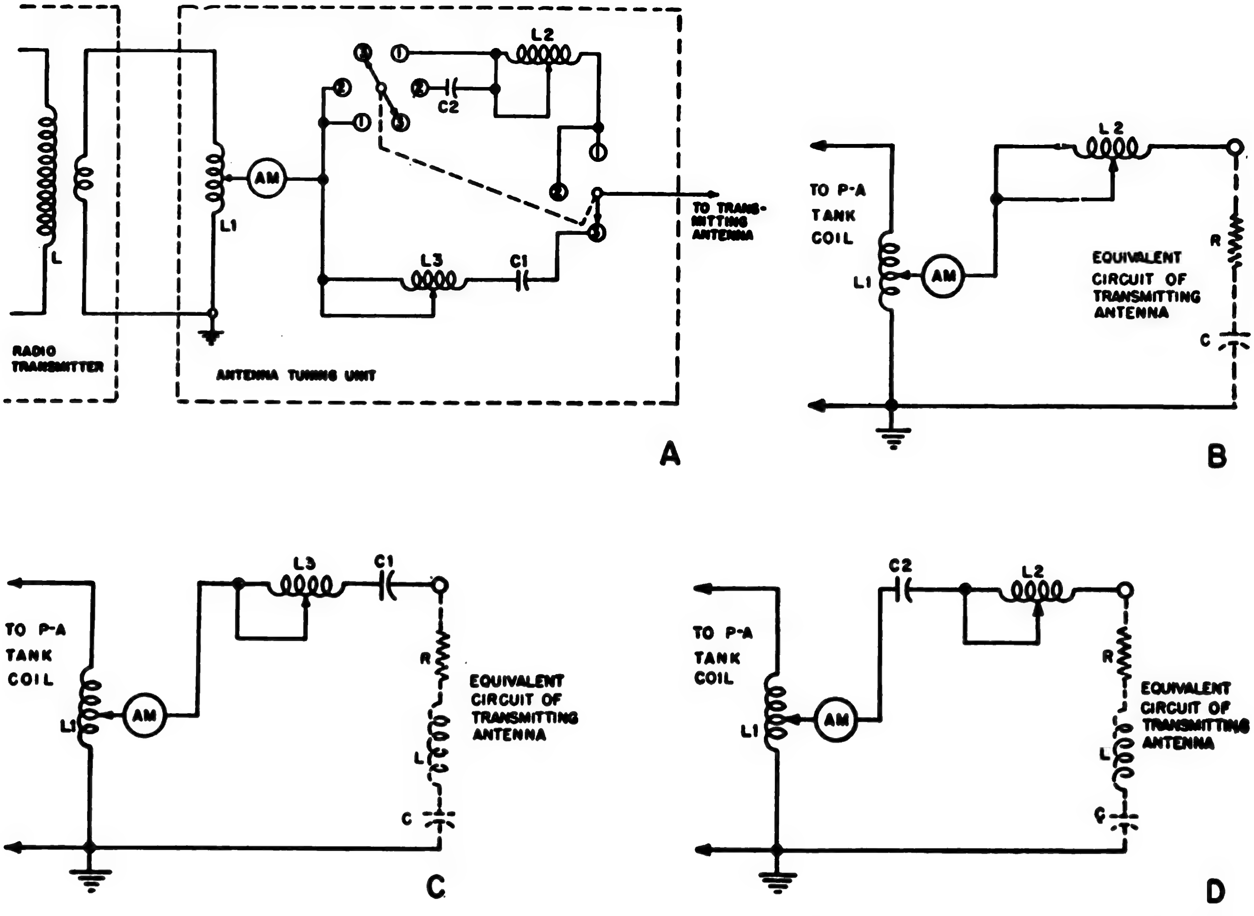

Figure 97. Antenna coupling circuits.

a maximum when the antenna is tuned properly.

(2) The circuit of the tuning unit when the range switch is set to position 3 is shown in C. Here a whip antenna is used and the frequency range covered is from 10 to 18 mc. From 10 to 12.5 mc, the reactance of the particular whip antenna used is capacitive; from 12.5 to 18 mc, the reactance is inductive. At approximately 12.5 mc, the antenna is purely resistive. The antenna is tuned to resonance by varying the inductance of the high-frequency loading coil, *L3*, which is made variable by a movable tap controlled from the front panel. Capacitor *C1* provides the added capacitance necessary when operating at frequencies between 12.5 and 18 mc. Its effect is neutralized by using more turns in *L3* when the transmitter is operating in the 10- to 12.5-mc range.

(3) The circuit of the tuner when adjusted for use with a long wire antenna is shown in D. The switch is now in position 2. The antenna is either capacitive or inductive depending on its length and operating frequency. As in previous adjustments, the antenna is tuned to resonance by varying the series inductance.

66. Multitube Transmitter Circuits

a. Mopa Transmitter with Hartley Oscillator (fig. 98).

(1) The oscillator develops an r-f voltage across the tank circuit comprising capacitor *C2* and inductor *L*. Coupling capacitor *C3* permits the r-f currents to flow to the amplifier while preventing the amplifier bias voltage supply E_C, from being short circuited by the oscillator inductor. This capacitor is tapped down on *L* to

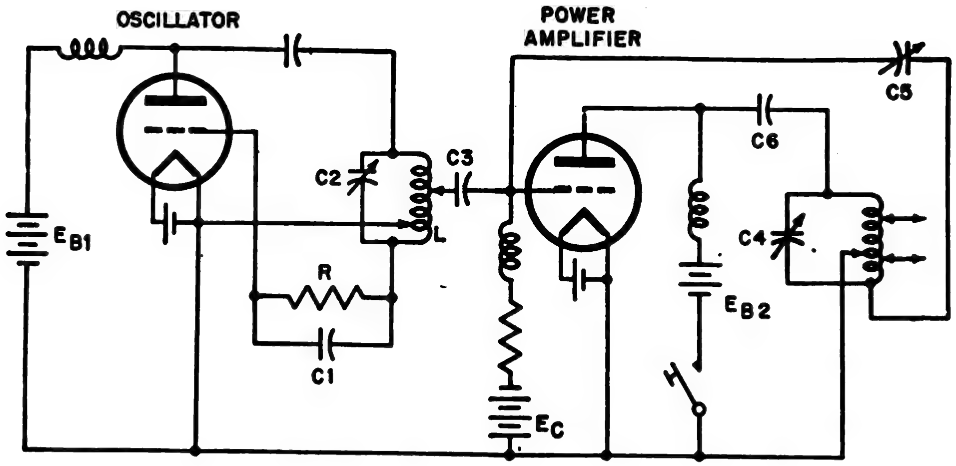

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Figure 98. Schematic diagram of mopa transmitter.

provide an efficient match between the oscillator output and amplifier input and to minimize loading on the oscillator. Plate voltages for the oscillator and amplifier are taken from power supplies E_{B1} and E_{B2}, respectively.

(2) The power amplifier uses a parallel fed plate circuit. Feedback voltage required for neutralizing the amplifier is taken from the lower end of the tank coil. The voltage is fed back through neutralizing capacitor *C*5. When the stage is neutralized, the capacitance of *C*5 is approximately equal to the grid-to-plate capacitance of the amplifier tube. Plate circuit keying is used.

b. High-Power High-Frequency Transmitter. Figure 99 illustrates many of the circuits described in this chapter. The high-power high-frequency transmitter is designed for 900 watt output at frequencies between 1.5 and 30 mc. Its circuit arrangement is similar to that of many transmitters used in military applications, an example of which is shown in figure 100. A top view of the same transmitter is illustrated in figure 101.

(1) *Exciter.* *V*1 (fig. 99) is an electron-coupled oscillator designed to tune concontinuously from 1.5 to 3.8 mc. Its screen and plate voltages are stabilized at 210 volts by the series connected VR (volt-regulator) tubes. Therefore, the oscillator is immune to frequency changes caused by changes in supply voltage. The oscillator stage is housed in a shielded, insulated compartment located within a larger shielded compartment housing the class A buffer amplifier and class C buffer amplifier or crystal oscillator.

(*a*) *V*2 is a class A buffer amplifier which is coupled to the oscillator through a modified impedance coupling. In this circuit, the usual r-f choke or tuned circuit is replaced by a resistor (100,000 ohms) in the grid circuit of *V*2. Because this tube operates class A, it presents a constant high impedance load to the oscillator. Therefore the oscillator load is constant, and its frequency is not affected by changes in loading in subsequent stages of the transmitter.

(*b*) The class A buffer, *V*2, feeds *V*3 which is used as a class C buffer amplifier or a crystal oscillator, depending on the position of switch *S*1. The plate of the class A buffer is coupled to a contact on *S*1 through a blocking capacitor. One section of the switch opens the high voltage lead to the master oscillator and buffer while the other section switches the grid of *V*3 from the plate circuit of *V*2 to one of the crystals. Therefore, *V*3 is converted from an r-f amplifier to an ordinary tetrode crystal oscillator.

(*c*) The exciter, consisting of *V*1, *V*2, and *V*3, can be used for controlling the frequency of almost any transmitter. The input power to the exciter is comparatively low and can be supplied by bat-

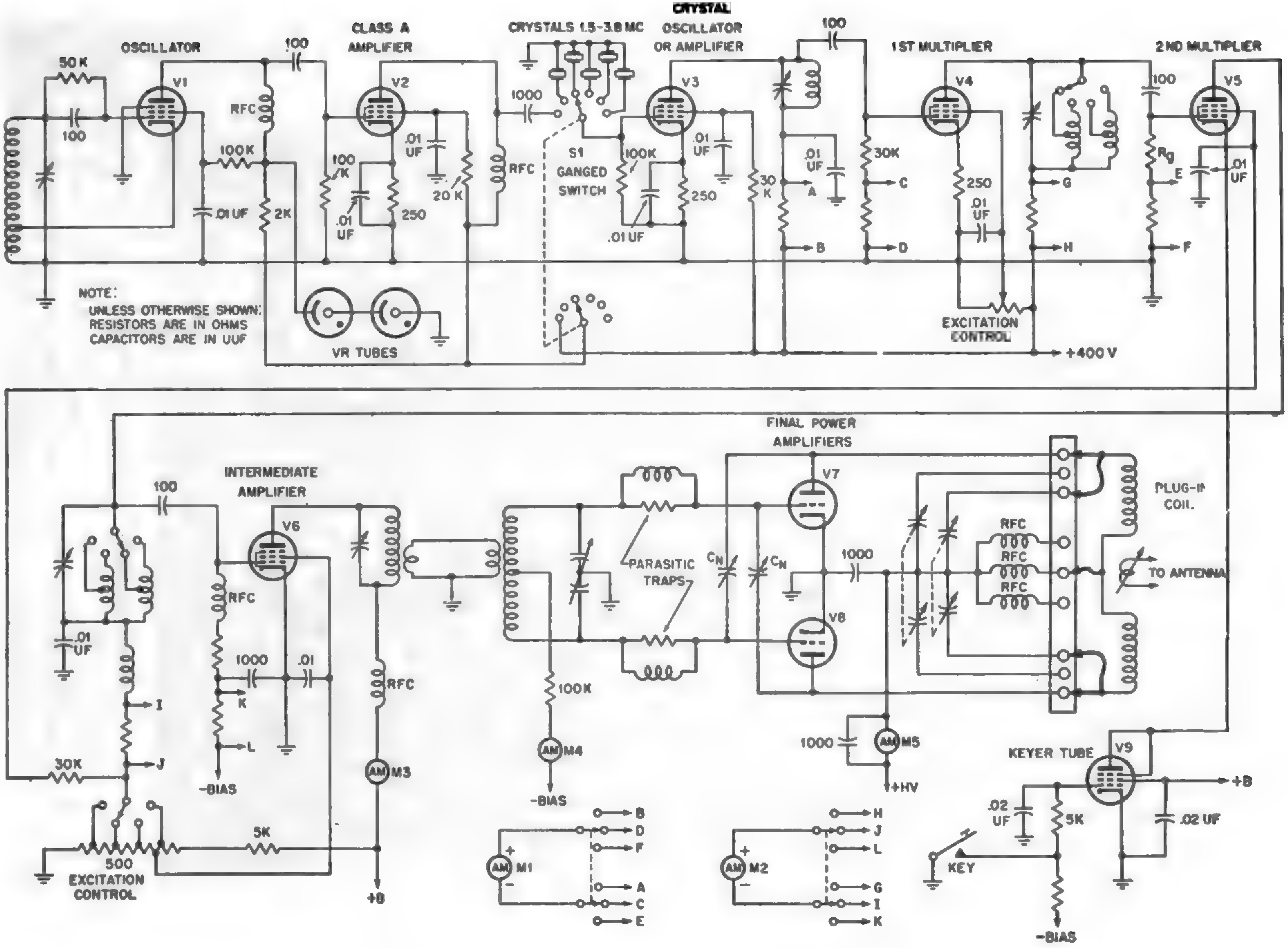

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Figure 99. Schematic diagram of high-frequency high-power transmitter.

Figure 100. Typical military transmitter.

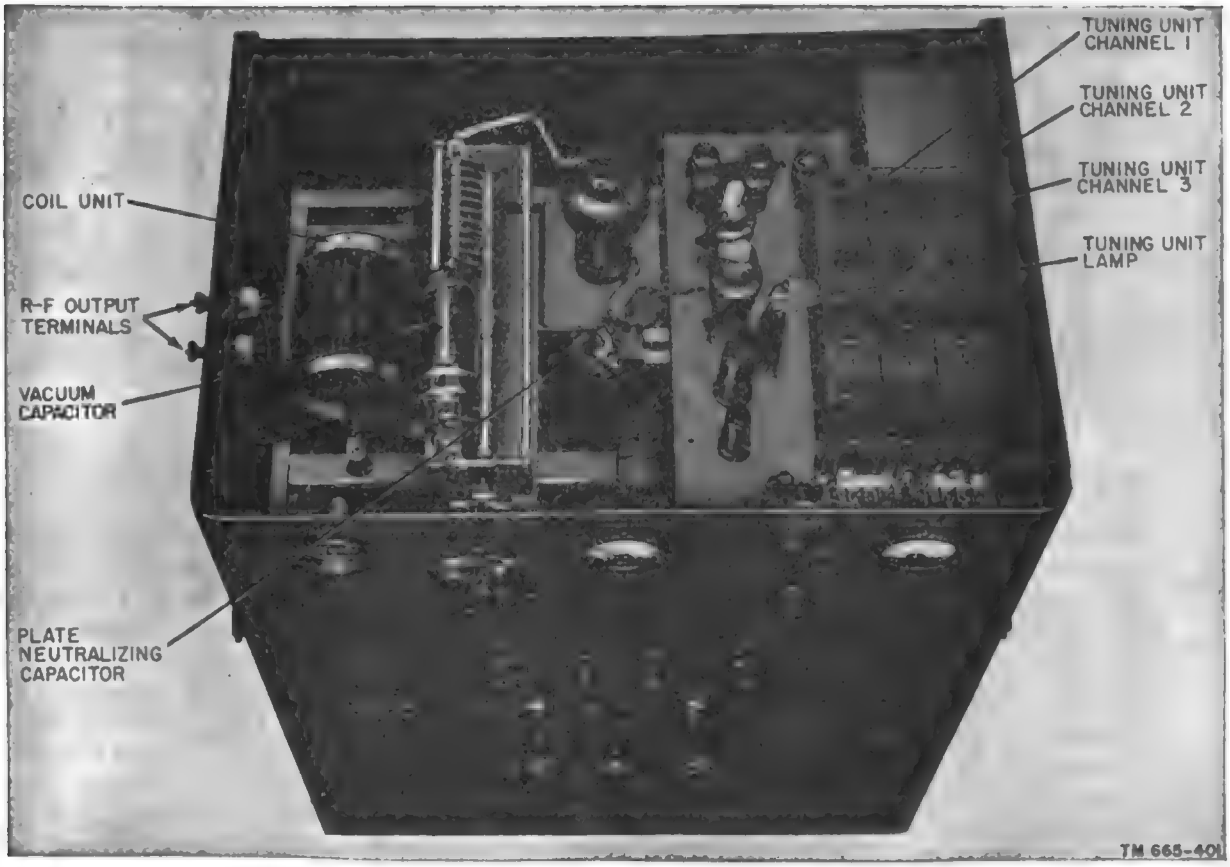


Figure 101. Top view of typical military transmitter.

teries, line operated power packs, hand- or motor-driven generators, or vibrator power supplies. Equivalent tubes having directly heated filaments, or miniature glass types, are used in the interest of saving space or reducing drain on the power supply. In some installations, it is desirable to have the exciter unit at a point remote from the operating position. For example, in fixed station installations the exciter may be on the operating desk next to the receiver and the transmitter amplifier circuits may be in another room. In such applications, the tank circuit of *V*3 usually is link coupled to the grid of the following stage.

(2) *Frequency multipliers.*

(*a*) Two multiplier stages, *V*4 and *V*5, have range selector switches which select the correct tank coil for a given tuning range. When the transmitter is operating between 1.5 and 3.8 mc, both tubes are operated straight through (without multiplying). Impedance coupling is used between *V*4, *V*5, and *V*6. Excitation to *V*5 and *V*6 is controlled by varying the screen and plate voltages of the preceding stage.

(*b*) By selecting the appropriate tank coils for the multiplier stages, it is possible to multiply the exciter frequency by 2, 3, 4, 6, 8, 12, or 16. Consequently, if it is desired to multiply the oscillator frequency by 6, one of the multipliers can be operated as a tripler and the other as a doubler. To multiply by 16, both tubes can be operated as quadruplers.

(*c*) The transmitter is keyed by means of an electron tube keying circuit in the cathode return circuit of *V*5. Under key up conditions, the keyer tube is cut off by a large amount of negative bias supplied by a battery or any regulated d-c source. Closing the key removes the blocking bias from *V*9. As a result, this tube and *V*5 both conduct. By inserting additional frequency multiplier stages between *V*5 and the following stage, this basic exciter and multiplier unit can be used in transmitters operating at much higher frequencies.

(3) *Intermediate amplifier.* The intermediate or driver amplifier, *V*6, is a medium power transmitting type beam power pentode capable of delivering up to 150 watts of output at frequencies up to 30 mc. Its purpose is to provide the driving power (approximately 80 watts) required by the final amplifier. Since pentodes and tetrodes are damaged easily by excessive excitation, provisions are made for metering the grid current and varying the excitation. *V*6 can deliver up to 150 watts and therefore can be used as the final amplifier of a transmitter delivering that amount of power. The only change required is to link couple the tank circuit to an antenna tuner instead of the grid circuit of *V*7 and *V*8 which comprise the 900-watt final power amplifier.

(4) *Final power amplifier.*

(*a*) Push-pull triodes *V*7 and *V*8, used in the final amplifier, deliver 900 watts output into the antenna. Plug-in coils are used in the plate circuit. To provide optimum *L-C* ratios on all tuning ranges, several variable capacitors are used in the plate circuit. The plug-in coils are equipped with jumpers to select the individual capacitors that may be required for a given inductance. Because it is difficult to get an r-f choke to operate efficiently over a wide range of frequencies, three chokes are used in the transmitter. A jumper on the coil selects the choke that is most effective in a given tuning range.

(*b*) The transmitter works into a conventional antenna tuner or into a doublet antenna. Coupling to the antenna or tuner is varied by changing the coupling between the plate tank coils and link coil. Conventional cross neutralization is used on the push-pull tubes.

(*c*) Power output can be increased by replacing the tubes used in the final power amplifier with tubes having a greater power output rating and by raising the plate voltage. Even greater power output from the transmitter is possible if the push-pull amplifier is used as a driver amplifier for an additional power amplifier.

(5) *Metering the transmitter.* The ability to measure grid and plate currents is important for the efficient operation of any transmitter. Circuit resonances are best indicated by meters in the plate and grid circuits. Full metering is particularly important in a multistage transmitter. Meter *M*1 measures the plate current of *V*3, and the grid currents of *V*4 and *V*5. *M*2 meters the plate currents of *V*4 and *V*5 and the grid current of *V*6. *M*3 measures the plate current of *V*6. Grid and plate currents of *V*7 and *V*8 are measured by *M*4 and *M*5, respectively.

67. Summary

a. Radiotelegraph (code) signals are sent out by a continuous wave transmitter.

b. The signals are produced by opening and closing one of the transmitter circuits by means of a telegraph key operated in accordance with a code.

c. A simple transmitter consists of an r-f oscillator to generate the signal and an antenna to radiate it into space.

d. Oscillator-type transmitters tend to be unstable and to have definite limits on the maximum power output and operating frequency.

e. When high power, good stability, and wide frequency range are required, one or more power amplifiers may be used between the oscillator and the antenna.

f. Coupling circuits which consist of combinations of inductance and capacitance are used to transfer energy between amplifier stages and between the power amplifier stage and the antenna.

g. Triode amplifiers require neutralization to prevent self-oscillation.

h. Oscillations are caused by energy fed back from plate to grid through the interelectrode capacitance of the tube.

i. The neutralizing system feeds to the grid a voltage equal in amplitude and opposite in phase to the voltage fed back through the tube.

j. Most radio-frequency power amplifiers operate class C for high efficiency.

k. Excitation voltage from the preceding stage must be sufficient to cause plate current to flow during the positive half cycles.

l. Oscillators are most stable when operating at low frequencies. Therefore, the oscillator often operates at a frequency considerably lower than the output frequency of the transmitter.

m. The frequency may be multiplied by a class C amplifier whose output is tuned to some harmonic of its input.

n. Frequency multipliers whose outputs are the second, third, and fourth harmonics of their input frequencies are called doublers, triplers, and quadruplers, respectively.

o. Frequency multipliers operate with grid bias voltage and grid excitation somewhat higher than that specified for normal class C operation.

p. The greater grid bias and excitation cause the plate current to flow for shorter portions of the excitation cycle.

q. The short plate-current pulses are distorted and have high harmonic content.

r. Keying can take place in any stage of the transmitter.

s. Keying the oscillator avoids backwaves but it is likely to cause chirps.

t. Keying following stages minimizes chirps but the backwave from the oscillator is likely to make break-in operation impossible.

u. Radiation of harmonics from the transmitter can cause serious interference to stations operating on frequencies that are multiples of the transmitter frequency.

v. Harmonics are minimized by using single-frequency antennas, low-power multipliers, adequate bypassing, and trap circuits tuned to the harmonic frequency.

w. Parasitic oscillations are spurious oscillations which occur at some frequency far removed from the frequency to which the transmitter is tuned.

x. Parasitics reduce power output from the transmitter and often damage capacitors and inductors in the parasitic circuit.

68. Review Questions

a. What are the types of emission?

b. What is a carrier wave?

c. Why is a carrier necessary?

d. What are the basic components of the simplest transmitter?

e. What is the objection to coupling an oscillator directly to an antenna?

f. What is a mopa transmitter?

g. What are the advantages of a mopa transmitter?

h. Why is a power amplifier necessary?

i. What are the general operating conditions for class C amplifiers?

j. Under what conditions is neutralization necessary?

k. Describe a simple neutralization indicator.

l. Draw a circuit showing shunt neutralization.

m. Describe the procedure to be followed when neutralizing an amplifier.

n. What is a frequency multiplier?

o. Is it unnecessary to neutralize a frequency multiplier?

p. Illustrate the basic interstage coupling systems and give one advantage and disadvantage of each system.

q. Draw circuits illustrating two methods of blocked grid keying. Which type is preferable? Why?

r. What is the purpose of a keying relay?

s. Describe how electron tube keying can be used in remote controlled transmitters.

t. Draw a circuit of a simple key click filter.

u. What is a parasitic oscillation?

v. What are the effects of parasitics?

w. How can harmonics be eliminated?

x. What are the effects of harmonic radiation?

y. Can improper tuning cause excessive harmonic radiation?

z. What is a Faraday shield?

aa. Why is an antenna tuner or coupler necessary?

CHAPTER 5

AMPLITUDE MODULATION

69. General

a. Another method of radio transmission, in contrast to c-w transmission, is accomplished by varying the carrier waveform in accordance with the variations in the intelligence to be transmitted. Using this method, speech, music, or any other form of intelligence, is first converted into alternating voltages, and these voltages, in turn, are superimposed on a carrier waveform and then transmitted. This varying process is called modulation. In practice, the frequency of the carrier wave is much higher than the highest modulating frequency.

b. In the basic block diagram of a modulated radio transmitter (fig. 102), the r-f oscillator generates the r-f frequency voltage. The output of the oscillator is amplified by a buffer stage, an intermediate power amplifier, and an r-f power amplifier before being radiated by the antenna. The source of modulating signal may be the output voltage of a microphone, a device which converts audio sounds into electrical voltages which vary at the frequency of the sounds—that is, at an audio frequency. The varying audio voltages are amplified in a modulator and are superimposed on the r-f carrier wave before being radiated by the antenna.

70. Types of Modulation

a. Amplitude Modulation. The process by which audio signal or modulating frequencies are impressed on an r-f carrier wave to vary its amplitude is called *amplitude modulation.* Figure 102 is a block diagram of an amplitude-modulated transmitter. The frequency and phase of the carrier is not affected by this type of modulation.

b. Frequency Modulation and Phase Modulation. Besides its amplitude, the carrier wave has two other characteristics that can be varied to produce an intelligence bearing signal. These are its frequency and its phase. The process of varying the frequency in accordance with the intelli-

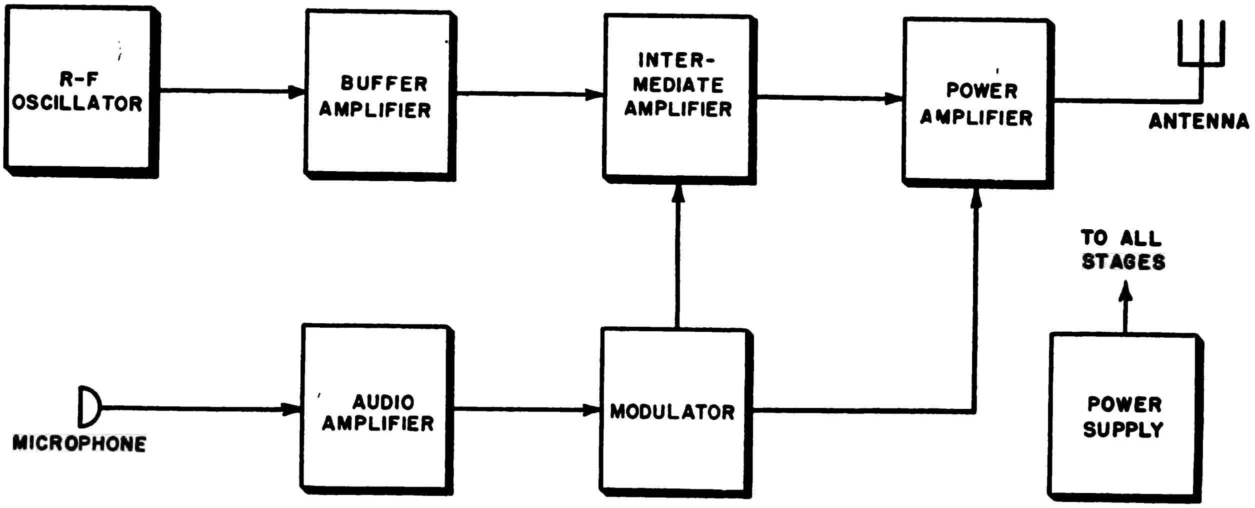


Figure 102. Basic block diagram of a modulated transmitter.

gence is f-m (frequency modulation), and the process of varying the phase is p-m (phase modulation). These two types of modulation are closely related. When frequency modulation is used, the phase of the carrier wave is indirectly affected. Similarly, when phase modulation is used, the carrier frequency is affected. A complete discussion of both types of modulation is given in TM 11–668.

71. Analysis of Amplitude Modulation

a. *Modulated Waveshape* (*fig. 103*).

(1) When an r-f carrier is modulated by a single audio note, two additional frequencies are produced. One is the upper frequency, which equals the sum of the frequency of the r-f carrier and the frequency of the audio note. The other frequency is the lower one, which equals the difference between the frequency of the r-f carrier and the frequency of the audio note. The one higher than the carrier frequency is the *upper side frequency;* the one lower than the carrier frequency is the *lower side frequency.* When the modulating signal is made up of complex tones, as in music, each individual frequency component of the modulating signal produces its own upper and lower side frequencies. These side frequencies occupy a band of frequencies lying between the carrier frequency, plus and minus the lowest modulating frequency, and the carrier frequency plus and minus the the highest modulating frequency. The bands of frequencies which contain the side frequencies are called *side bands.* The side band which contains the sum of the carrier and the modulating frequencies is known as the *upper side band;* the band which contains the difference of the carrier and the modulating frequencies is known as the *lower side band.* The space which a carrier and its associated side bands occupy in a frequency spectrum is called a *channel.* The width of the channel (or *bandwidth*) is equal to twice the highest modulating frequency. Consequently, if a 5,000-kc (kilocycle) carrier is modulated by a band of frequencies ranging from 200 to 5,000 cycles (.2 to 5 kc) the upper side band extends from 5,000.2 to 5,000.5 kc, and the lower side band extends from 4,999.8 to 4,995 kc. The bandwidth is then 4,995 to 5,005, or 10 kc. The bandwitdh is twice the value of the highest modulating frequency, which is 5 kc. This is illustrated in figure 103.

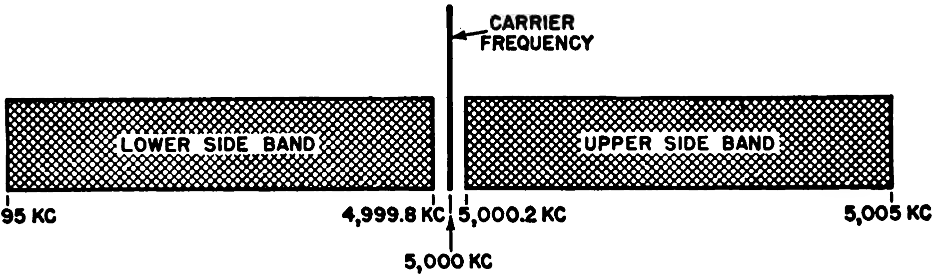
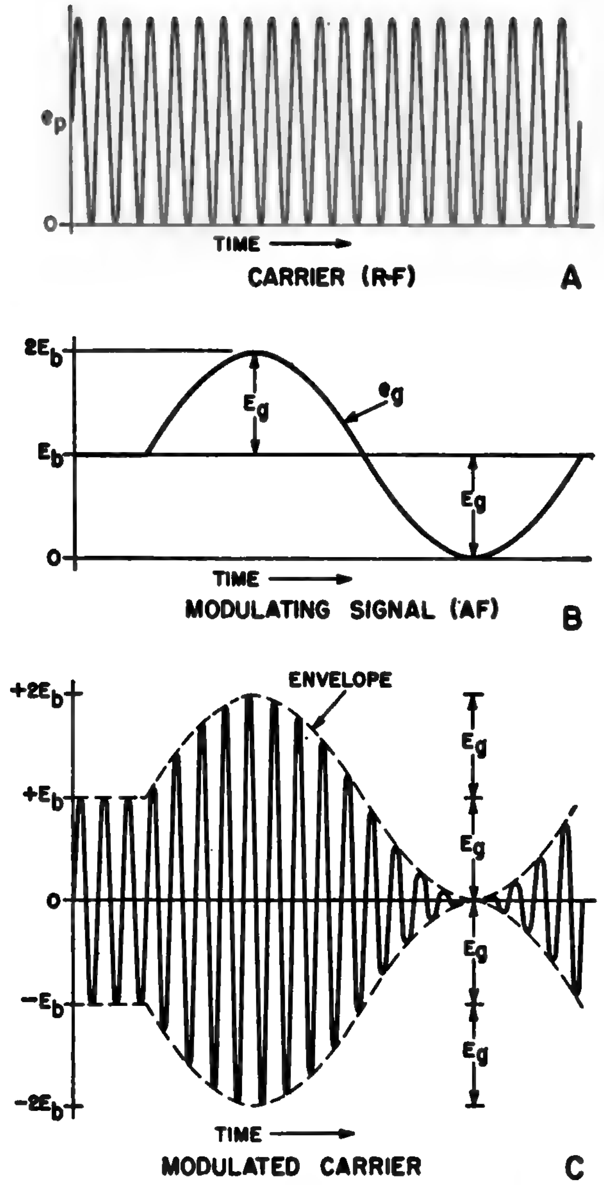


Figure 103. Side bands produced by amplitude modulation.

(2) The instantaneous plate voltage, e_p, of a carrier wave in a Class C amplifier is represented by the pulses shown in A of figure 104. The d-c plate voltage, E_b, is shown with the sine-wave modulating voltage, e_g, varying around it, so that plate voltage varies from zero to twice the value of E_b or $2E_b$. The peak value of the modulating voltage is represented by E_g. When e_p is varied in amplitude at a rate determined by e_g, the pattern in C results. The outline of the modulated carrier wave is shown by the dashed lines joining the tips of the successive r-f carrier pulses, and is called the *envelope.* The dashed lines appearing in the upper and lower sections of the modulated carrier correspond exactly to that of the modulating signal. The peak-to-peak amplitude of the modulated carrier varies from $+2E_b$ to $-2E_b$ or $4E_b$. This is an



A. Plate-current pulses produced by an unmodulated carrier.
B. Effect of superimposing a large a-c voltage on a d-c voltage.
C. Modulated envelope of a sine-wave modulated carrier under full modulation.

Figure 104. Modulation of an r-f carrier.

ideal condition where no distortion of the modulating signal exists.

b. Percentage of Modulation.

(1) The *depth* or *degree* of modulation of a carrier wave is dependent on the amplitude of the envelope as compared with the amplitude of the carrier. If the amplitude of the envelope is twice as great as the amplitude of the carrier, then the modulated waveform is said to be *fully*, or *100 percent* modulated. If the envelope amplitude is less than twice the carrier amplitude, the waveform is less than 100 percent modulated. The percentage of modulation, M, can be computed from one of the following formulas:

$$M=\frac{E_{max}-E_{car}}{E_{car}}\times 100\%$$

and

$$M=\frac{E_{car}-E_{min}}{E_{car}}\times 100\%$$

where

E_{max} is the maximum amplitude of the envelope,

E_{min} is the minimum amplitude of the envelope,

E_{car} is the amplitude of the carrier.

This formula is valid only for waveforms which are not overmodulated. An overmodulated waveform is one whose percentage of modulation is greater than 100 percent.

(2) A of figure 105, shows a modulating signal, and B is the modulated carrier. By substituting in the modulation formulas the voltage values given in the figure, the percentage of modulation, M, equals

$$M=\frac{E_{max}-E_{car}}{E_{car}}\times 100\%$$

$$M=\frac{150-100\times 100\%}{100}=50\%,$$

and

$$M=\frac{E_{car}-E_{min}}{E_{car}}\times 100\%$$

$$M=\frac{100-50}{100}\times 100\%=50\%.$$

Consequently, the percentage of modulation is 50 percent.

(3) If the peak of the modulating signal equals the d-c plate voltage (100 volts), the modulated carrier varies from 0 volt to 200 volts. This is shown in figure 106. Again, applying the modulating formulas,

$$M=\frac{E_{max}-E_{car}}{E_{car}}\times 100\%$$

$$M=\frac{200-100}{100}\times 100\%=100\%$$

$$M=\frac{E_{car}-E_{min}}{E_{car}}\times 100\%$$

$$M=\frac{100-0}{100}\times 100\%=100\%.$$

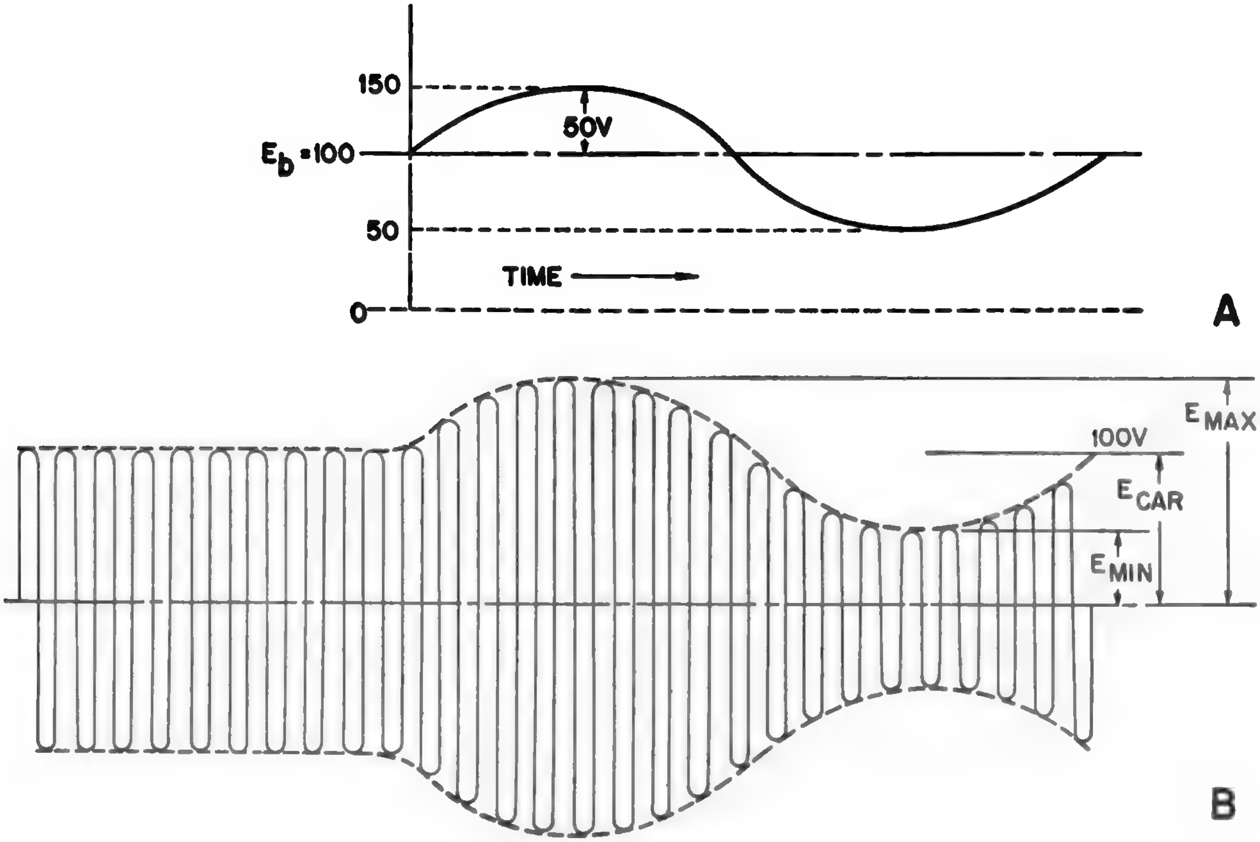


Figure 105. Illustrating 50-percent modulation.

The percentage of modulation is 100 percent. Whenever the modulating signal varies between zero and twice the d-c plate voltage, there is 100-percent modulation.

(4) A transmitter usually is operated so that the average percentage of modulation approaches, but does not exceed, 100-percent modulation. That is, it is better to operate at 75 percent than at 50; 85 percent is better than 75; and so on up to 100 percent. This is true for the following reasons: The signal-to-noise ratio of the received signal is higher when the modulation percentage approaches 100 percent. Strong side bands make the received signal less susceptible to interference from stations operating on the same channel. Because of the increased power in the side bands, a fully modulated transmitter transmits a greater distance for a given carrier power.

c. *Overmodulation.*

(1) Consider the case where a modulator delivers an audio voltage of 150 volts peak to an r-f modulated amplifier operated with 100 volts d-c on its plate. The two voltages add to produce an instantaneous peak of 250 volts on the positive half of the modulation cycle. On the negative half cycle, the plate voltage will swing to 50 volts negative, thus cutting off the r-f amplifier for the period that the plate voltage is below the zero line, as in A of figure 107. This condition produces an overmodulated carrier, as in B, in which area A is the period during which the r-f modulated amplifier is cut off. This break in the r-f output of the transmitter produces distortion at the receiver. This condition exists whenever the peak a-f signal voltage exceeds the d-c plate voltage of the modulated amplifier.

(2) Whenever an amplifier is modulated in excess of 100 percent the momentary inter-

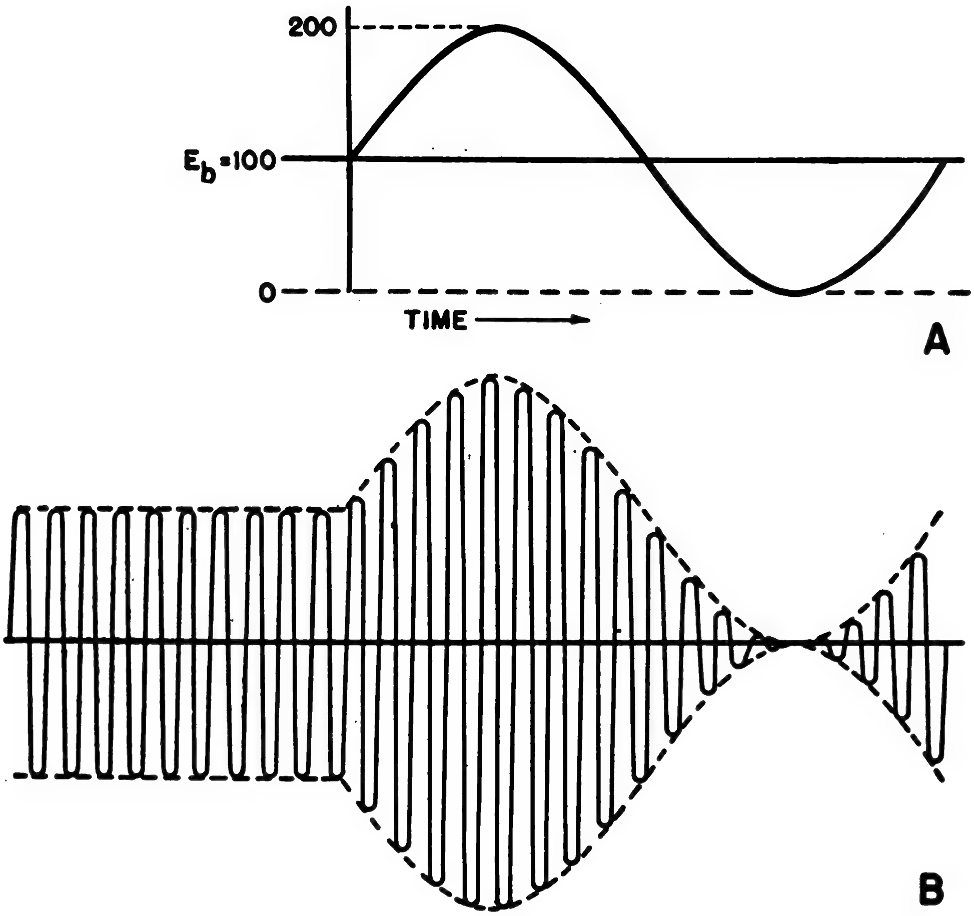


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Figure 106. Illustrating 100-percent modulation.

ruption of plate current in the r-f modulated amplifier produces serious changes in the wavelength of the original modulating frequencies. New frequencies and harmonics are created. Their number and intensity vary with the degree of overmodulation. These spurious modulating frequencies produce additional side bands which extend far beyond the normal bandwidth and cause interference to stations on adjacent channels.

(3) Overmodulation also can cause serious damage to a transmitter that is not adequately protected by fuses or circuit breakers. The sum of the peak audio and the d-c plate voltages may be sufficiently high to break down the insulation in modulation transformers, plate bypass capacitors, and r-f chokes.

d. Distribution of Power in an Amplitude-Modulated Wave.

(1) The power in an amplitude-modulated wave is divided between the carrier and the side bands. The carrier power is constant (except in cases of overmodulation) and so the side-band power is the difference between the carrier power and the total power in the modulated wave. When a carrier is modulated by a single sinusoidal tone, the total power output is found from the formula

$$P_{mod}=\left(1+\frac{m^2}{2}\right)\times P_{car}$$

where

P_{mod} is the total power in the modulated wave,

m is the degree of modulation,

P_{car} is the power in the carrier.

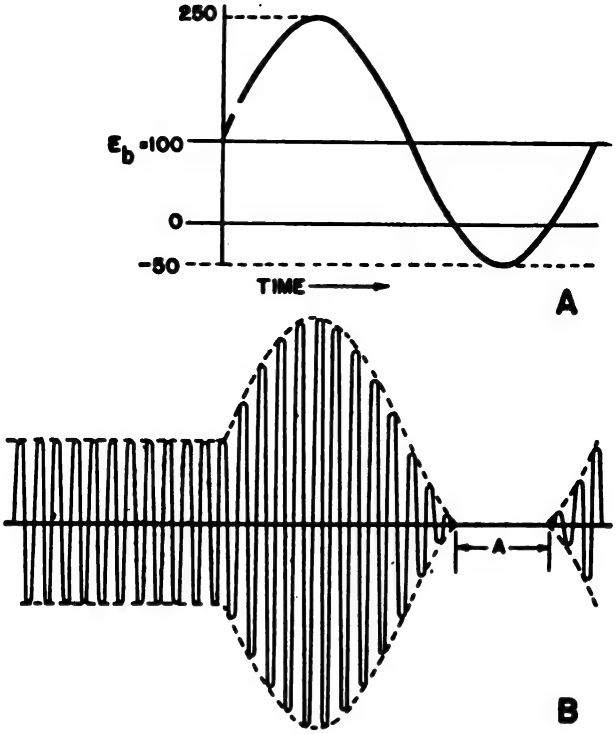

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Figure 107. Overmodulation.

Assuming that a 500-watt carrier is modulated 100 percent, the power in the signal is

$$\left(1+\frac{(1)^2}{2}\right)\times 500=750 \text{ watts}$$

Of this total, 500 watts are in the carrier and 250 watts are in the side bands. The percentage of side-band power 250/750 times 100 percent equals 33.3 percent. Of the 250 watts of side-band power, there are 125 watts in each side band and the power content of each therefore is 16.6 percent of the total power output with 100-percent modulation.

(2) The available side-band power takes a marked drop when the average percentage of modulation is well below 100 percent. This is shown by modulating the carrier only 50 percent when the power in the carrier is 500 watts.

$$P_{mod}=\left(1+\frac{(.5)^2}{2}\right)\times 500=562.5 \text{ watts}$$

The total modulated power is now 562.5 watts. Since 500 watts exist in the carrier, only 62.5 watts of power remain in the side bands. Since 62.5 watts are one-fourth the value obtainable with 100-percent modulation, it is seen that reducing the modulation of 50 percent causes a 75-percent reduction in the available side-band power. Since all of the intelligence being transmitted is contained in the side bands, the desirability of a high percentage of modulation becomes evident.

72. Stages of Amplitude-Modulated Transmitter

a. General. Referring to figure 108, it is seen that a feeble voice signal entering a microphone is amplified by several a-f speech amplifiers and also by the a-f modulator. The r-f oscillator produces the r-f carrier wave which is amplified by the r-f buffer amplifiers. The outputs of the a-f modulator and r-f buffer amplifiers are mixed in the final r-f amplifier to produce the modulated carrier wave.

b. Radio-Frequency Circuits. Essentially, the r-f section of an amplitude-modulated transmitter consists of an r-f oscillator and several r-f amplifiers. In many cases, buffer amplifiers are used between the oscillator and the r-f amplifiers. As mentioned in the previous chapter, buffer amplifiers are used to isolate the oscillator from the following stages to minimize changes in oscillator frequency with changes in loading. Frequency multipliers are used to raise the oscillator frequency of the transmitter to the desired carrier frequency. It is desirable to have the oscillator operate at a comparatively low frequency for reasons of stability. Intermediate r-f amplifiers may be used to increase the driving power of the final r-f amplifier. The stage that the modulator feeds is known as the modulated r-f amplifier.

(1) The a-f voltages developed by a microphone or other signal source are comparatively low, usually less than 1 volt, whereas the d-c potentials applied to the tube electrodes are high. The addition of the low a-c voltage to the high d-c potentials on the tube electrodes results in a very small variation in the power output. Therefore, it is necessary to amplify the alternating signal voltage, audio frequencies for radiotelephone, and modulated c-w transmitters, to a level high

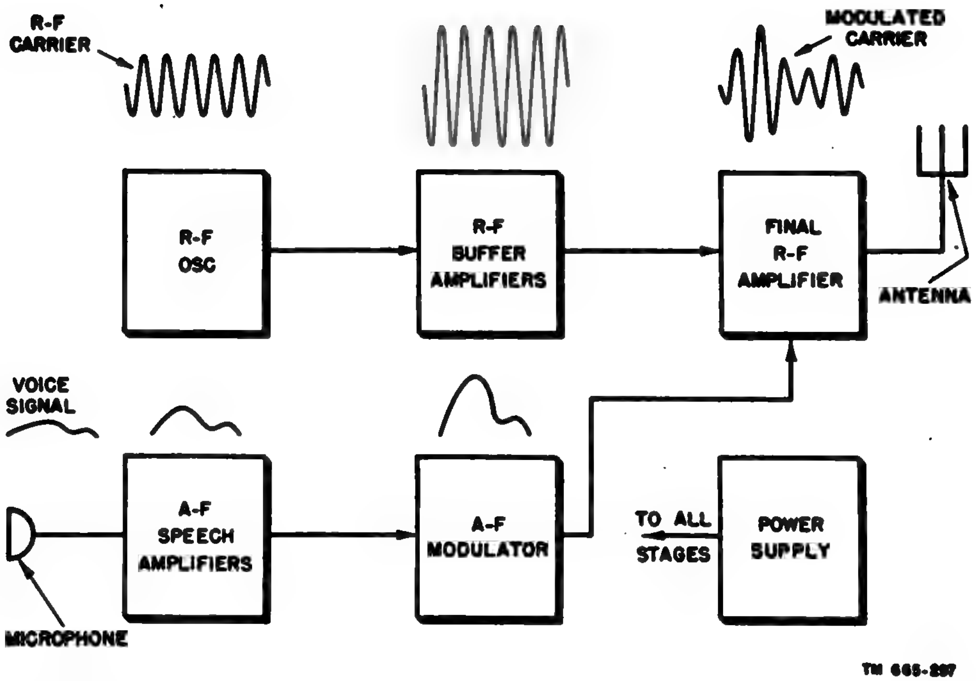

Figure 108. Block diagram of an amplitude-modulated radiotelephone transmitter and waveshape.

enough to cause considerable variation in the power output of the transmitter.

(2) The audio amplification usually takes place in at least two stages. The a-f speech amplifier is a class A voltage amplifier. The output of this stage drives a second stage which may be a voltage amplifier or a power amplifier, depending on the required input power to the modulator. In a small transmitter, the speech amplifier and modulator may be combined in one stage. In transmitters, the modulator is usually an audio power amplifier. It can be any type of power amplifier that will deliver the required amount of undistorted audio power to the modulated r-f amplifier. It may be operated class AB, or class B. If it is a class AB or class B amplifier, it must be a push-pull stage.

c. Power Supply. As in c-w transmitters, d-c operating power can be supplied by dry batteries, storage batteries, power lines, generators, or dynamotors. Many transmitters have a single high-voltage supply which is capable of supplying enough power for the r-f and a-f circuits of the transmitter. This is particularly true of most small transmitters used in the field and in mobile installations. High-power transmitters and those designed for semiportable and fixed station work often have a separate power supply for the audio equipment.

d. Figure 109 shows the rear view of a typical military transmitter (also shown in figures 100 and 101). The lower chassis is the power supply; the middle chassis is the speech amplifier and modular section, and the top chassis contains the r-f stages.

73. Systems, Methods, and Levels of Modulation

A radio carrier may be amplitude-modulated in various ways, the two principle systems being known as *constant efficiency, variable input modulation* and *variable efficiency, constant input modulation. Method of modulation* usually refers to the electrode or element of the r-f amplifier to which the modulating voltage is applied.

a. Constant Efficiency, Variable Input Modulation. In this system, the efficiency of the modulated stage remains constant, and the output is varied by varying the power input to the stage. In *plate modulation,* the most commonly used method, the modulating voltage is impressed on the d-c supply voltage to the plate of one of the r-f amplifiers of the transmitter. The output of

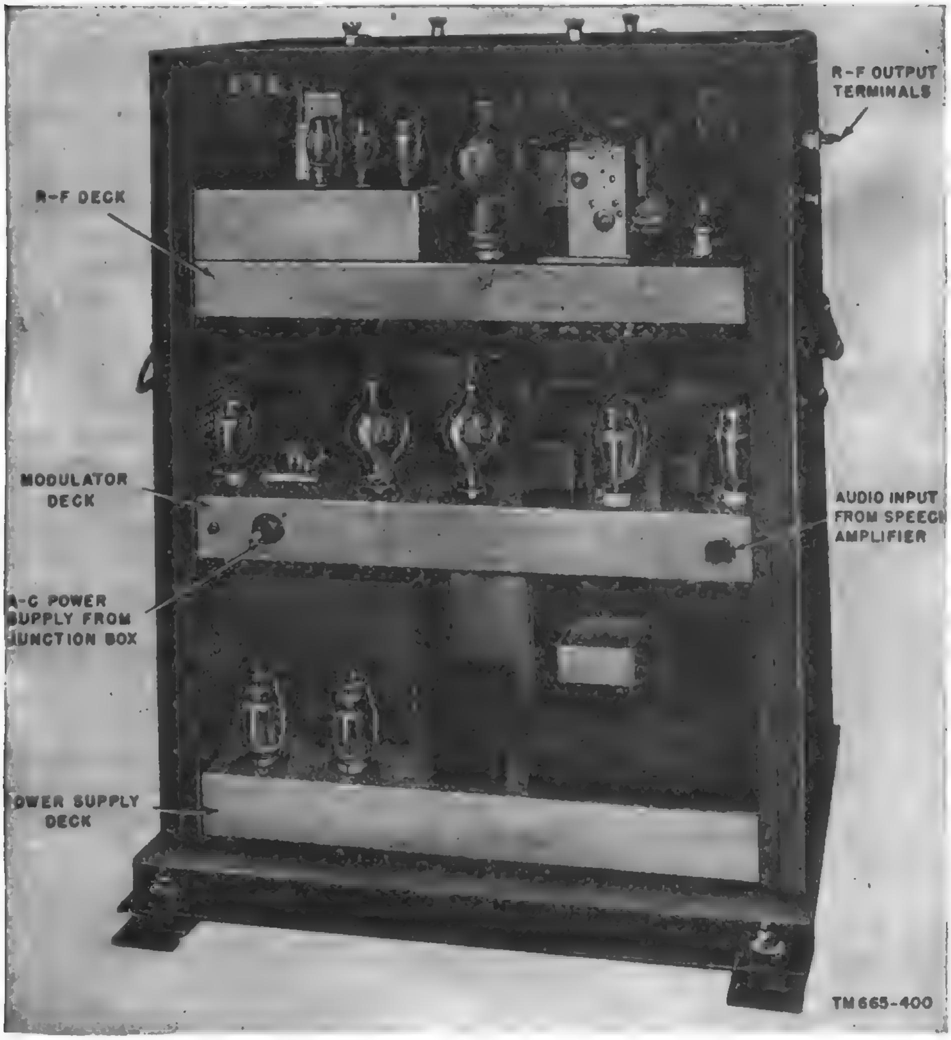

Figure 109. Rear view of military transmitter.

the modulated stage is varied by the varying input voltage, but its efficiency remains constant.

b. Variable Efficiency, Constant Input Modulation. In the following methods, the d-c input voltage to the modulated stage is constant and the output is varied by varying the efficiency. Application of the modulating voltage to the control grid of an r-f amplifier is called *grid modulation* or *grid bias modulation*. Pentode type power amplifiers can be modulated by applying the modulating voltage to the suppressor grid to produce *suppressor modulation*, or to the screen grid to produce *screen grid modulation*. Screen grid modulation can be applied also to tetrode type power amplifier tubes. *Cathode modulation* is a method in which the modulating voltage is applied to the cathode circuit of the modulated stage.

c. Levels.

(1) *High level modulation.* Since the modulating voltage is applied to the final r-f amplifier in high level modulation, the stages preceding it need not be perfectly linear. Therefore they may be operated class C with operating potentials adjusted for the desired circuit efficiency and gain. The final stage always is operated class C. The over-all efficiency of such a transmitter is high. A disadvantage of high level modulation is that comparatively high audio power is needed and several stages of voltage and power amplification may be required in the speech amplifier and modulator circuits.

(2) *Low level modulation.* In this method, modulation takes place in a buffer or intermediate power amplifier stage, and modulating voltage is applied to a stage preceding the final amplifier. The r-f amplifiers which follow the modulated stage must be operated in such a manner that their a-c output voltages are amplified, undistorted replicas of the modulated r-f voltages applied to their grids. Since little a-f power is required to modulate the carrier fully, the a-f section of the transmitter can be made comparatively simple. A disadvantage of this system of modulation is that the modulated stage must be followed by linear r-f amplifiers. Since lower efficiency usually is obtained from linear amplifiers, the efficiency of a low level modulated transmitter is low as compared with that of a high level modulated transmitter using the same type of tubes and identical d-c operating voltages. Some specialized types of linear amplifiers can be used for higher-than-normal efficiency but, because of difficulties in adjustment and operation, their use is not general.

74. Constant Efficiency Modulation—Plate Modulation

This method is the most commonly used of those suitable for high level amplitude modulation. It permits the transmitter to operate with high efficiency. It is simplest to apply and easiest to adjust for proper operation. The modulator, usually operated push-pull, is coupled to the plate circuit of the final r-f amplifier. For 100-percent modulation, the modulator must supply enough power to the r-f plate circuit to cause the instantaneous voltage on the plate of the modulated amplifier to vary between zero and twice the d-c operating plate voltage.

a. Heising Modulation.

(1) Any system of plate modulation may be called Heising modulation, after its inventor. However, popular usage of the term *Heising modulation* usually is limited to the choke coupled arrangement shown in figure 110. Other plate modulation circuit arrangements are considered to be transformer-coupled and are identified by the class of operation used in the modulator tubes. The system of plate modulation commonly known as Heising modulation consists of a class A modulator coupled to the plate supply circuit of the modulated r-f amplifier through a modulation choke coil, *L*. The a-f voltage on the plate of the modulated r-f amplifier is supplied from the modulator plate through the choke coil. Consequently, the r-f plate voltage can be varied by varying the voltage on the modulator plate. The modulator operates as an a-f power amplifier with the plate circuit of the modulated r-f amplifier as its load. The output of the modulator is super imposed on the d-c supplied to the modulated r-f amplifier. For 100-percent modulation, the modulator must develop a peak a-c voltage equal to the d-c voltage on the plate of the amplifier without modulation.

(2) The a-f signal is applied to the modulator grid through transformer *T*1. The voltage applied to the primary of this transformer is usually the output of a speech amplifier which brings the microphone voltages up to the level required at the modulator grid. As the modulator grid is made less negative on one half cycle of the modulating signal, the modulator plate current increases. This increased flow of current through inductor *L* induces a voltage in it which opposes the increase in current. Being 180° out of phase with the original voltage, this induced voltage subtracts from the voltage on the modulator plate. Since the plate of the modulated r-f amplifier is essentially tied to this point, its plate voltage, and consequenly its r-f power output, are reduced.

(3) Conversely, the modulator grid becomes more negative on the next half cycle of the modulating signal. This causes a reduction in the modulator plate current. The voltage induced in *L* is now a minimum which permits the plate voltage and r-f power output of the modulated r-f amplifier to be a maximum.

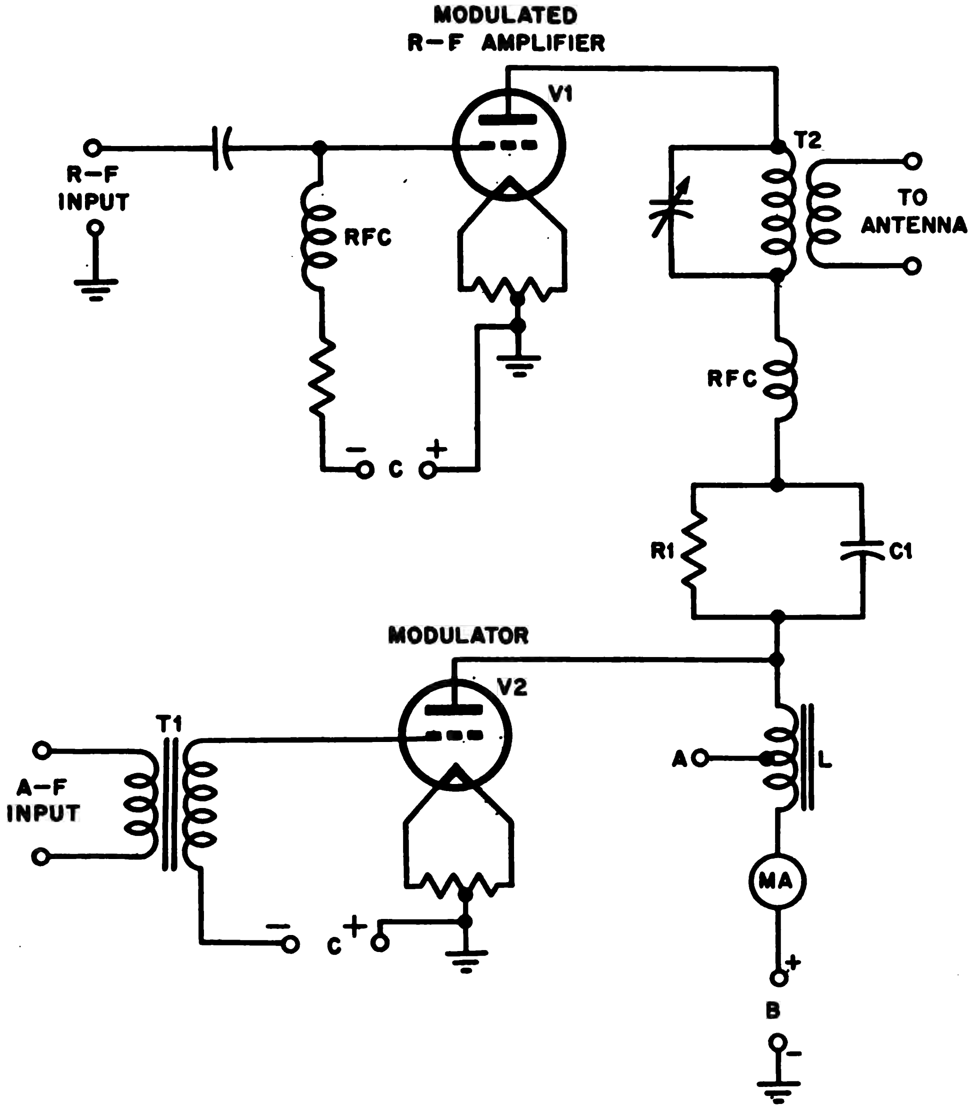

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Figure 110. Basic Heising modulation system.

(4) For 100-percent modulation, the audio voltage developed across *L* must have a peak value equal to the d-c voltage on the modulated r-f amplifer plate. The instantaneous plate voltage varies from zero to twice the d-c plate voltage of the modulated r-f amplifier. The modulated r-f amplifier operates at some fixed value of efficiency, which means that the r-f power output is always directly proportional to the power input. The effective a-f output voltage of a class A amplifier is never equal to its d-c plate voltage because its operating range is restricted to the linear portion of the dynamic grid voltage plate-current characteristic curve for distortion free operation. Consequently, the d-c plate voltage on the modulated r-f amplifier must be reduced to a level equal to the maximum a-c peak voltage which can be developed with negligible distortion. The plate voltage for the r-f amplifier is dropped by resistor *R*1 which is bypassed by capacitor *C*1. The capacitive value of *C*1 is selected so that it prevents a negligible reactance to audio frequencies.

(5) Instead of reducing the d-c plate voltage applied to the modulated r-f amplifier or driving the class A modulator into the

high distortion region in an effort to obtain 100-percent modulation, an autotransformer arrangement can be used. In this case, the modulator plate is connected to some point *A* on modulation coil *L*. Resistor *R*1 and capacitor *C*1 then are omitted since a portion of *L* reduces the d-c plate voltage on the modulated r-f amplifier. A comparatively low a-c voltage developed across the modulator section of *L*, through autotransformer action, results in a higher a-c voltage applied to the plate of the modulated r-f amplifier. By selecting the proper tapping point on *L*, it is possible to obtain a turns ratio which results in a perfect match between the two stages so that maximum audio output and transfer of modulation power is obtained. The proper impedance match between the modulated r-f amplifier and modulator also provides for freedom from distortion over wider modulation levels.

(6) *Impedance-capacitance coupling* is another method of coupling a class A modulator to the modulated r-f amplifier (fig. 111). A separate modulation choke *L*2, is connected in series with the d-c plate supply lead to the modulated r-f amplifier. An audio-coupling capacitor, C_c, connects the plate side of choke *L*1 in the modulator plate lead to choke *L*2. This method of coupling seldom is used because of difficulties in matching the impedances of the modulator and modulated r-f amplifiers stages.

b. Transformer Coupling.

(1) In the most widely used method of coupling between a modulator and a modulated r-f amplifier (fig. 112), the modulator is transformer coupled by *T*1 to the plate circuit of the modulated r-f amplifier. The modulator plate current flows in the primary and the modulated r-f amplifier plate current flows in the secondary of *T*1. The audio power developed by the modulator appears in series with the d-c voltage that is applied to the modulated r-f amplifier. This produces a resultant voltage whose instantaneous value increases and decreases at an audio rate determined by the modulating frequency.

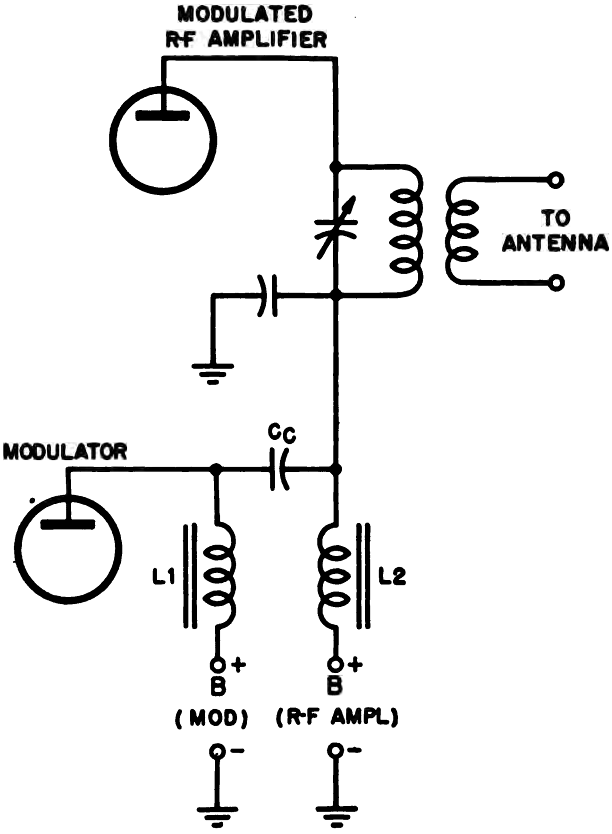

Figure 111. Plate modulation using impedance coupling.

(2) The modulator power output and the turns ratio of transformer *T*1 must be such that the a-c voltage on the plate of the r-f amplifier varies from zero to twice the d-c operating voltage for 100-percent modulation. The turns ratio is adjusted so that the modulator operates into its proper load impedance. The modulator tube can be operated class A, class AB, or class B. In all except class A, the modulator must be a push-pull stage.

(3) The discussion thus far has considered only the use of triodes as modulated r-f amplifiers. Pentode and tetrode r-f amplifiers are used also. However, a modulated r-f amplifier cannot be modulated satisfactorily by inserting the modulating voltage in series with its plate. Part of the modulating voltage must be applied also to the screen grid, because the plate current of a modulated r-f amplifier is

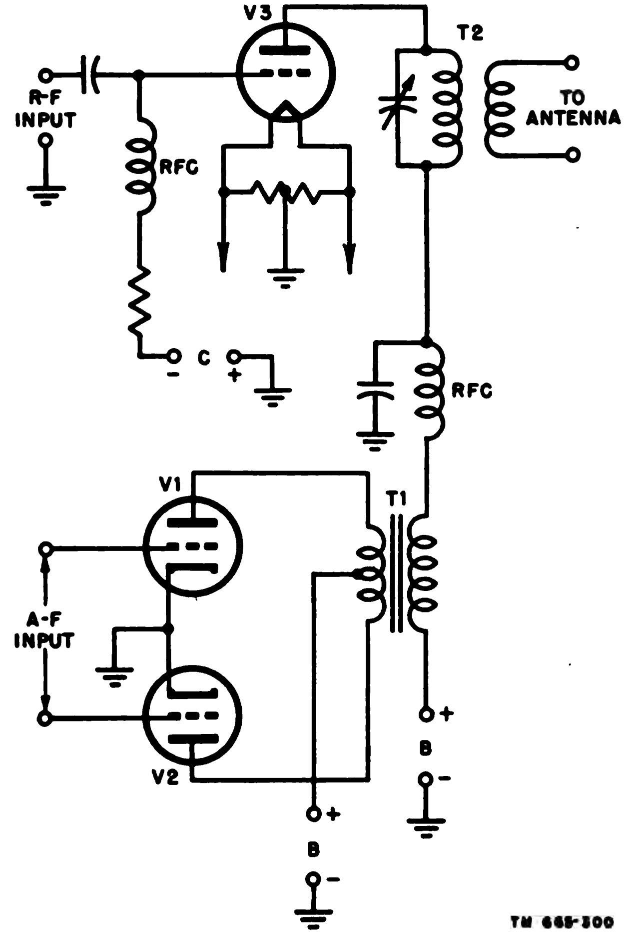

Figure 112. Plate modulated r-f amplifier with transformer coupling between modulator and modulated r-f amplifier.

determined by the screen grid voltage as well as the plate voltage. Therefore, in order to assure a linear variation in plate current, the modulating voltage must be applied to both the plate and the screen grid.

(4) One method of modulating the screen grid simultaneously with the plate is shown in figure 113. In this circuit, dropping resistor *R*1 is the screen-grid dropping resistor. *C*3, the plate bypass capacitor, has a low reactance to r-f. *C*1 bypasses the audio voltage around the screen grid dropping resistor, and *C*2 is the r-f bypass capacitor for the screen grid. Since the modulator must supply power to modulate the screen and plate circuits of the modulated r-f amplifier, the load impedance formula for pentode and tetrode tubes is

$$Z_p=\frac{E_{bb}}{I_p+I_{sg}}\times 1{,}000$$

where

E_{bb} is the d-c plate voltage,

I_p the d-c plate current in milliamperes, and

I_{sg} the d-c screen grid current in milliamperes.

c. Plate-Modulation Considerations. Five factors must be taken into consideration when modulating a class C amplifier if the modulated signal is to have minimum distortion and the circuits are to operate with a relatively high efficiency.

(1) The r-f excitation to the modulated r-f amplifier must be adequate. It should have sufficient amplitude to cause the r-f current in the plate tank circuit to follow the plate voltage as it varies under modulation. If the plate voltage is decreased to one-half its value, the plate current

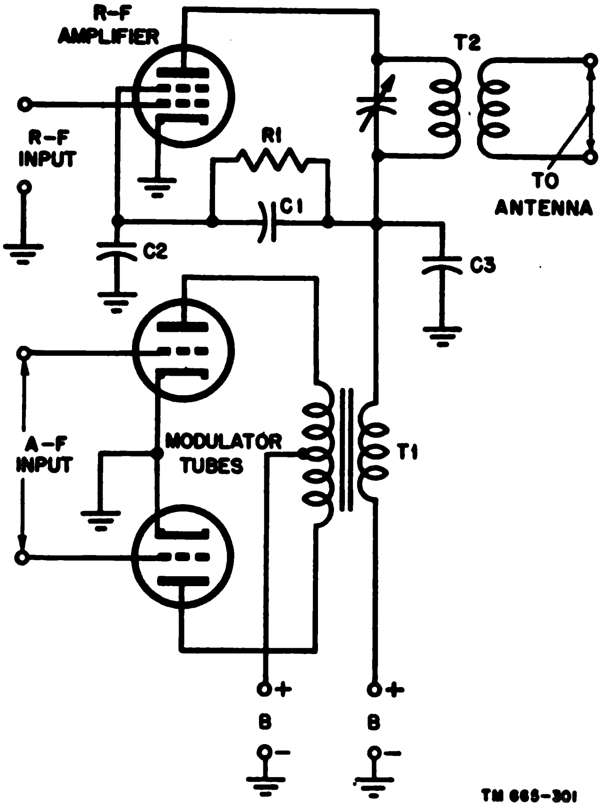

Figure 113. Method of plate modulating a screen grid tube.

drops likewise; if the plate voltage is doubled, the current increases in the same proportion. Since the plate voltage rises to twice its normal value at 100-percent modulation, the r-f excitation must be sufficiently high to cause the plate current to do likewise. The r-f excitation should be increased when necessary to maintain a linear relationship between the instantaneous power output and the instantaneous plate voltage for all modulation percentages up to 100 percent. The excitation preferably should be obtained from a source having relatively poor regulation, but not so poor as to affect the modulation adversely. This prevents the grid current, and hence the power dissipated in the grid, from becoming excessive when the plate voltage approaches zero under heavy modulation. The grid current increases as the grid is driven more positive and as the minimum plate voltage approaches zero. Therefore, if the maximum grid voltage is greater than the minimum plate voltage, secondary emission takes place at the plate. The secondary electrons from the plate are attracted to the grid and, thereby, will increase the grid current and the amount of power dissipated by the grid. If the driver for the modulated r-f amplifier has poor regulation, the excitation voltage tends to drop off when the load impedance changes. The use of grid-leak bias on the r-f modulated amplifier tends to stabilize the maximum grid potential. With grid-leak bias, any tendency to change the maximum grid voltage produces a large change in the grid current. This increased grid current develops a higher negative voltage drop across the grid resistor and the maximum signal voltage is effectively reduced.

(2) The grid bias should be at least twice the tube cut-off value. The major portion of the bias usually is obtained from a grid leak resistor. Sufficient fixed bias or cathode bias is used to limit plate current to a safe value in the absence of excitation. The reactance of the grid bypass capacitor is usually at least twice the resistance of the grid leak resistor at the highest modulation frequency. If this were not the case, the distortion would become pronounced because the grid bias cannot follow the plate circuit variations produced by modulation.

(3) The tank circuit of the modulated r-f amplifier is designed to have a relatively low *Q;* otherwise, the resonance curve may be sharp enough to attenuate the higher frequencies present in the upper side band. Although the *L-C* ratio should be high for good plate circuit efficiency, it should not be too high in a plate modulated transmitter because considerable flywheel effect is required for good linearity under modulation. Generally, if two coils are available for tuning to a desired frequency, the one requiring the higher tuning capacitance for resonance is used.

(4) The modulation transformer is designed or adjusted to match the modulator tubes to a load determined by the plate voltage and plate current of the modulated r-f amplifier. Therefore, if the plate voltage is fixed, the antenna coupling and loading should be adjusted so that the modulated r-f amplifier is drawing current which results in the desired load being presented to the modulator.

(5) The d-c power input to the modulated r-f amplifier for plate modulation is less than that rating for the same tube in using c-w. This is true because the power applied to the plate of the modulated r-f amplifier is 1.5 times its normal value and the tube must dissipate 50 percent more power than when the carrier is unmodulated. Since the tube operates at these peak values for such short periods of time, the power input ratings for radiotelephone service usually are about two-thirds the permissible value for c-w.

75. Variable Efficiency Modulation

a. Grid Bias Modulation.

(1) Class C amplifiers also may be modulated by applying the modulating voltage to the control grid instead of the plate. A circuit of a typical grid modulated r-f

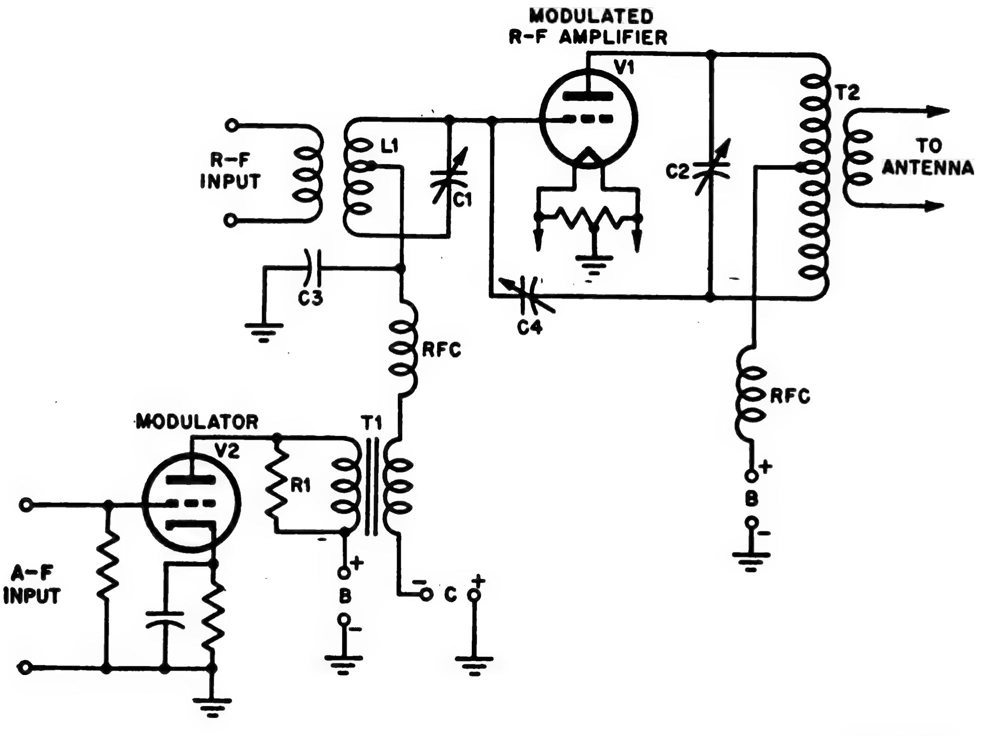

Figure 114. Circuit for grid-bias modulation.

amplifier is shown in figure 114. The modulator is coupled to the grid circuit of the modulated r-f amplifier by modulation transformer *T*1. The modulating signal currents flow in the primary and the modulated r-f amplifier grid currents flow in the secondary of *T*1. The fixed grid bias voltage for the modulated r-f amplifier is provided by a *C* supply. The r-f choke, RFC, in the grid circuit of *V*1, and capacitor *C*1 prevent the r-f current in the *L*1*C*1 tank circuit from entering the modulator and the power supply.

(2) Applying the a-f modulating voltage throught *T*1 to the grid of the modulated r-f amplifier does not change the average grid voltage, since the average value of a sine voltage is zero. This being the case, the average plate current and average plate power input are constant. Since the average power input is constant, the increase in power output is obtained by increasing the efficiency of the amplifier, or, in other words, decreasing the power loss within the tube. The operating conditions for linear modulation are so made that the efficiency of the stage is approximately 33 percent in the absence of modulation. During full modulation, the power output increases to 1.5 times its unmodulated value, and the plate current efficiency increases approximately 51 percent. The modulated carrier output is approximately one-fourth as great as the same tube adjusted for plate modulation.

(3) The d-c bias for a grid modulated r-f amplifier is the same as in normal c-w operation, but the excitation voltage is somewhat lower so that the grid will not be driven to the zero grid bias point. The modulating a-f voltage causes the instantaneous grid voltage to vary at an audio rate, thus shifting the operating point of the grid circuit and varying the efficiency and output of the stage. The change in grid voltages places a variable load on the stage driving the modulated r-f amplifier (the driver) and on the plate of the modulator tube. This change in loading causes distortion. Changes in modulator loading are minimized by placing a shunting resistor, *R*1, across the primary of the modulation transformer, *T*1. This resis-

tor should be equal to, or somewhat larger than, the normal load into which the modulator should work for normal output. To prevent changes in the loading on the driver, this stage should be capable of delivering several times the required driving power. The driver is loaded so that it delivers considerably more power than is required to the grid circuit of the modulated amplifier.

(4) The modulator tube must be operated as a class A amplifier. Its power output can be small, since it is necessary only to vary the negative grid bias slightly. The power output of the modulator is very low because the grid is not permitted to swing positive and draw grid current.

(5) An advantage of grid modulation is that comparatively little audio power is required for modulation purposes. This advantage is nullified by its many disadvantages. The efficiency of a grid modulated amplifier is low and it is difficult to obtain a high degree of modulation without severe distortion. Furthermore, a larger than usual modulated r-f amplifier tube is required for a given power output, because the limited r-f excitation makes it impossible to obtain anywhere near the normal power output from the tube. Grid modulated transmitters seldom are used in military service. Figure 114 shows a triode used as the modulated r-f amplifier, but tetrodes or pentodes may be used also.

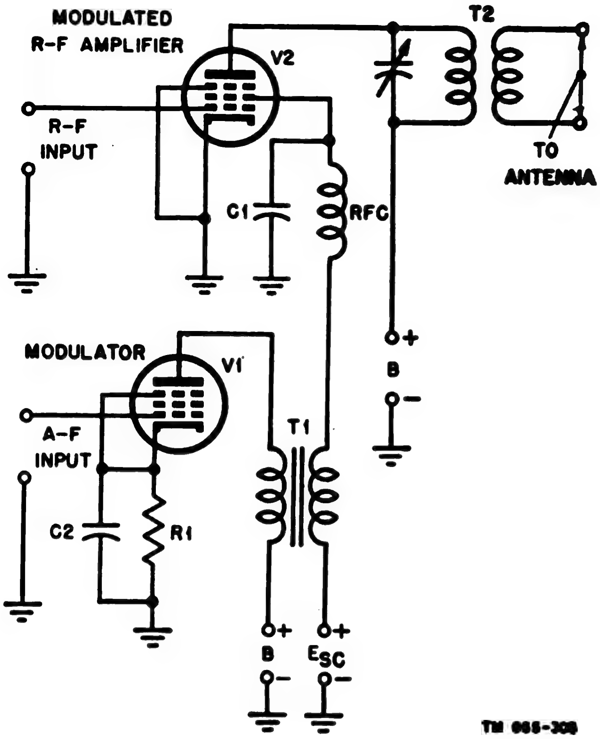

Figure 115. Circuit for screen grid modulation.

b. Screen Grid Modulation.

(1) Screen grid modulation is used to some extent in low power transmitters and in cases where space and power for a class B plate modulator are not available. In the typical screen modulated amplifier shown in figure 115, the d-c screen grid voltage is applied through the secondary of modulation transformer *T*1, the primary of which is connected to the plate of the modulator tube. Consequently, the modulating voltage is superimposed on the screen grid of the modulated r-f amplifier. The r-f choke, RFC, in the screen grid of the modulated r-f amplifier and capacitor *C*1 prevent r-f currents from entering the modulator and d-c power supply, where they may cause feedback. Capacitor *C*2 is the usual cathode bypass capacitor used to prevent degeneration in the modulator. Resistor *R*1 is a cathode return resistor for the bias voltage.

(2) The a-f power required for screen grid modulation is somewhat greater than that for grid bias modulation. The modulating a-f power is approximately one-quarter of the power input to the screen under normal c-w operation. The peak audio voltage is approximately equal to the d-c screen voltage which is adjusted to one-half the value used for c-w operation.

c. Suppressor Grid Modulation. Figure 116 shows the circuit of a suppressor grid modulated r-f amplifier in which the output of the modulator appears in the secondary of modulation transformer *T*1, which is in series with the suppressor grid of the modulated r-f amplifier. Capacitor *C*2 and r-f choke RFC prevent r-f currents from flowing through the secondary winding of *T*1 into the modulator and power-supply circuits. *C*2 has a low reactance to r-f and a high reactance to a-f; its average value is approximately .002 microfarad or smaller. Resistors *R*1 and *R*2 are the screen

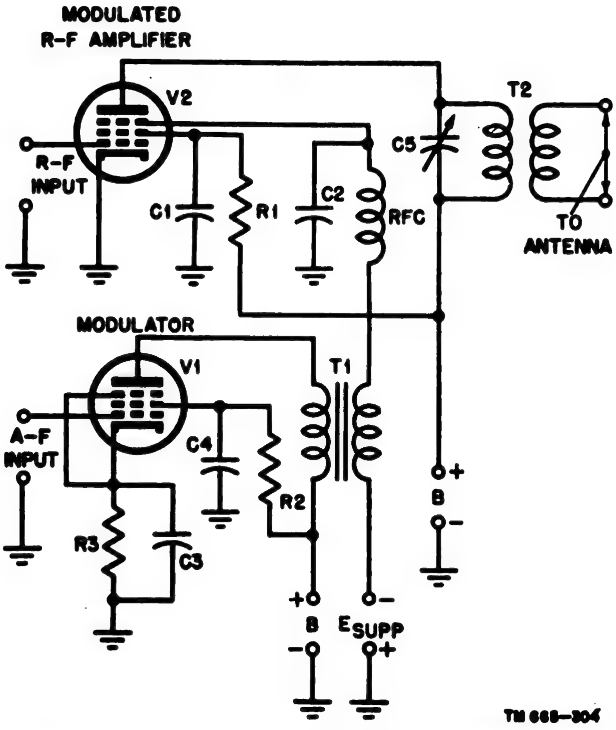

Figure 116. Circuit for suppressor grid modulation.

grid dropping resistors for the a-f and r-f tubes. They are bypassed by capacitors *C*1 and *C*4. Resistor *R*3 provides cathode bias voltage to the modulator stage; it is bypassed by capacitor *C*3 to prevent degeneration. *C*5 and the primary of *T*2 comprise the tank circuit in the modulated r-f amplifier.

d. Cathode Modulation.

(1) The modulator in figure 117 is coupled to the cathode circuit of the modulated r-f amplifier (in this case to the heater circuit) through modulation transformer *T*1. When a cathode tube is used as the modulated r-f amplifier, the secondary of *T*1 is connected to the cathode of the tube, instead of to the center tap on the filament transformer. The operating bias for the modulated r-f amplifier is applied between the C-minus and C-plus terminals. *C*1 is the grid bypass capacitor, *C*2 and *C*3 are filament bypass capacitors, and *C*7 is the plate bypass capacitor. *C*5, *C*6, and the primary of *T*2 make up

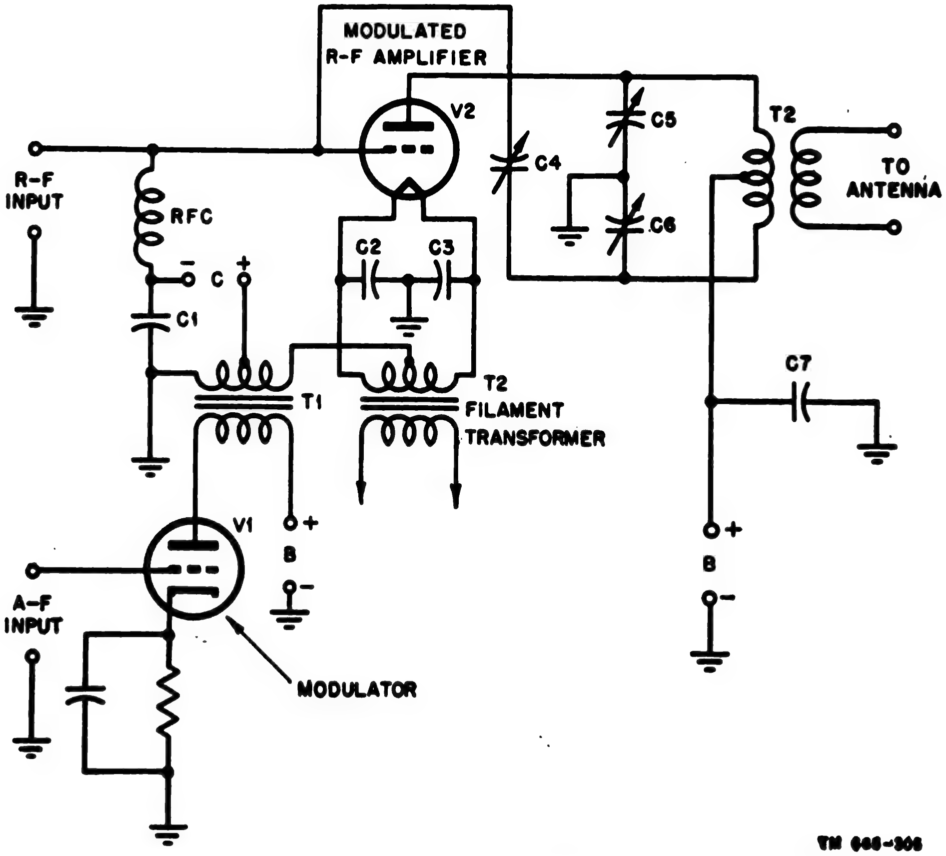

Figure 117. Circuit for cathode or center tap modulation.

the r-f tank circuit. *C*4 is a neutralizing capacitor. The r-f choke, *RFC*, prevents r-f currents from entering the modulator and power supply.

(2) Cathode modulation, sometimes called *center tap modulation* (fig. 117), is a combination of plate and control grid modulation. The efficiency of some cathode modulated r-f amplifiers can be made to approach the efficiency of the average plate modulated amplifier. The average efficiency of a grid modulated stage ranges from 30 to 40 percent; a well designed plate modulated amplifier has an efficiency of approximately 78 percent. Since cathode modulation is a combination of these two methods working in phase, it is possible to obtain a wide range of efficiency by adjusting the relative percentage of modulation.

(3) The modulation transformer, *T*1, supplies an optimum match between the cathode circuit of the r-f modulated amplifier and the plate of the modulator tube. The d-c grid bias of the cathode modulated r-f stage can be supplied by any of the conventional means but provisions usually are made for varying the bias to compensate for moderate variations in excitation. The r-f grid excitation should not be too high, since this would cause difficulty in obtaining the desired amount of grid modulation. The grid excitation is approximately half that required for plate modulation. If grid-leak bias is used alone, the value of the grid-leak resistor should be approximately six times larger than that required for c-w operation. The tuned circuit in the plate of the modulated r-f amplifier should have a *Q* of approximately 10 to 15 so that its harmonic output is low and the flywheel effect permits good linearity. The antenna loading is such that a further increase in loading causes a slight drop in antenna current. For optimum performance, the grid excitation should be adjusted for minimum plate dissipation with maximum power in the antenna.

76. Grounded Grid Amplifiers

a. The *grounded grid* amplifier was developed as the answer to the problem of neutralization of r-f amplifiers at high frequencies. In the normal circuit arrangement, the input r-f signal is applied between the grid and the cathode and taken off between the plate and cathode. In the grounded grid amplifier, also called an *inverted amplifier* or *common grid amplifier*, the control grid is grounded for r-f. The r-f input signal, as shown in figure 118, is applied through transformer *T*1. Capacitance coupling to the preceding stage may be used also. The r-f signal output appears in the secondary of *T*2. *C*1 and the primary of *T*2 comprise the plate tank circuit of the amplifier.

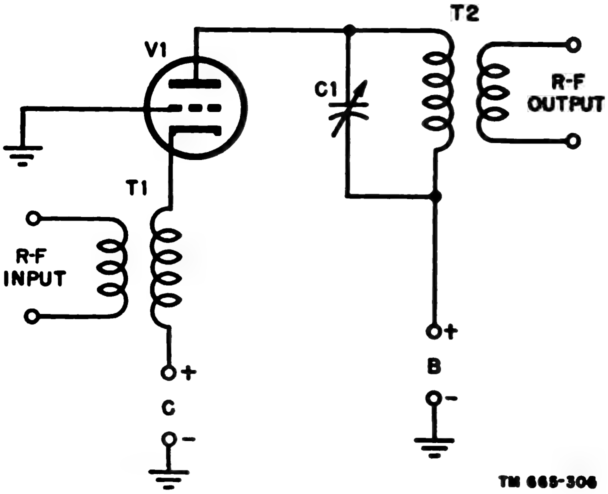

Figure 118. Grounded grid amplifier

b. The grounded grid acts as a shield to reduce the plate-to-cathode feedback capacitance in the same manner that the screen grid isolates the plate and cathode in a pentode or tetrode. In the conventional circuit, the suppressor and screen grids of tetrodes and pentodes reduce the feedback capacitance to the point where neutralization is seldom necessary up to frequencies in the neighborhood of 100 mc. At frequencies of several hundred megacycles, the screen- and suppressor-lead inductance makes it impossible to hold these leads at zero r-f potential and oscillation is likely to occur. In this case, grounded grid amplifiers are used.

c. As the operating frequency of a radio transmitter is increased, conventional circuit arrangements must be changed. The plate and grid leads begin to act as small inductances which effectively reduce the effect of the normal neutralizing capacitor. The frequency band over which the neutralization, once adjusted, can be maintained becomes progressively smaller, until the amplifier cannot be stabilized above a particular frequency. Furthermore, the normal neutralizing capacitance adds to the output capacitance of the tube, thus narrowing the effective r-f bandwidth and reducing the efficiency of the circuit because of excess circulating currents outside of the tank circuit. In the grounded-grid amplifier, the output capacitance is limited to the plate-to-cathode capacitance (plus stray capacitances) and greater operating bandwidths are possible, as well as higher efficiency caused by the lower circulating currents outside the tank circuit.

d. Another characteristic of the grounded grid amplifier is that the instantaneous r-f signal voltage between cathode and ground is in phase with the instantaneous r-f voltage developed between plate and cathode. These voltages appear in series across the load. Driving power requirements for a grounded grid amplifier are greater than for the same tube used as a conventional amplifier, because the driver supplies some of the output power appearing at the load of the grounded grid stage. However, this added power, which may be up to 10 times the driving power requirements of a conventional amplifier, is not lost, but simply transferred to the output circuit of the grounded grid amplifier.

e. Plate modulation of a grounded grid amplifier cannot be obtained at a modulation level of 100 percent. When a grounded grid amplifier is plate modulated, the output current and plate voltage are linear in respect to each other until about 60-percent modulation is reached. As the modulator output voltage exceeds this level, modulation becomes nonlinear. This is caused by the fact that the r-f driving voltage and d-c supply voltage are in series across the load; plate current does not drop to zero until the plate voltage reaches a negative value equal to the peak r-f driving voltage. However, frequency modulation, rather than amplitude modulation, generally is used at the very high frequencies for which the grounded grid circuit is particularly suited, so that this disadvantage is not a practical consideration in the use of the circuit.

77. Audio Components and Circuits

a. The audio section of an a-m transmitter converts sound waves into audio voltages and currents. It usually consists of a microphone and a series of electron tube a-f amplifiers to raise the output of the microphone to a power level sufficient to modulate the transmitter by the chosen method. With grid, screen, or suppresor modulation, the output power level is comparatively low; with plate modulation, it may vary from one-third to one-half the d-c power input of the modulated r-f stage. Knowing the voltage or current developed by a microphone used in the manner for which it was designed, and knowing the power output required from the modulator, it is possible to select the number and type of a-f amplifiers which will develop the required power with the least distortion.

b. There is little fundamental difference between the audio circuits used in modulators and those used in radio receivers, public address amplifiers, intercommunicators, and similar systems. In these devices, the power output may range from 1 watt for a small portable radio to several hundred watts for a public address system designed to cover a large outdoor area. A modulator may develop a power output ranging from 1 watt to several thousand watts, depending on its driving power. The output of an audio system generally is coupled to the load through a transformer; a radio or public address amplifier has an output transformer designed to match it to a loudspeaker, whereas the output of a modulator must be matched to a modulated r-f amplifier. Almost any public address amplifier which delivers the required audio power can be used as a modulator simply by replacing its output transformer with a modulation transformer which matches the load presented by the modulated r-f amplifier.

c. The criterion of radio communication is intelligibility of speech. This objective differs from the standards required in public address work and broadcasting, where naturalness of speech and tone and quality of music is important. For understandable speech, the voice frequencies between 100 and 2,500 cps are saitsfactory. Frequencies above and below these limits add to the naturalness of speech, but they do little to add to the intelligibility. Another most important consideration is the bandwidth of the channel used in communications. This bandwidth is directly proportional to the audio frequencies being transmitted (fig. 103). Therefore, if the voice frequencies transmitted are limited to those in the usable speech range, the channel width is reduced, and more stations can be operated in a given band of frequencies without causing mutual interference. Furthermore, frequencies outside the useful speech range absorb some of the side-band power which could be used to add more strength to the useful voice frequencies. For these reasons, the speech amplifiers of communication transmitters often include design features which accentuate these speech frequencies which contribute to intelligibility and attenuate (reduce) all others.

78. Microphones

a. General.

(1) The most commonly used microphone is one which converts the variations in air pressure produced by the human voice or a musical instrument into an electrical voltage or current of the same frequency and corresponding amplitude. Another type responds to vibrations by direct contact, rather than to the sounds produced by vibrations. Microphones may be designed to be selective in their freqency response. Those used for broadcast purposes, recording work, and some types of public address work, have uniform output in the range of frequencies from 30 to 10,000 cps and higher. The frequency response of communication type microphones often is limited to approximately 75 to 4,500 cps. Other design considerations involve the distance between the microphone and the sound source, as well as the ability of a microphone to pick up sound uniformly from different angles. Just as the intensity of sound waves decreases with the distance from the source, so the sensitivity of a microphone decreases as the distance between it and the sound source is increased. Maximum sound pick-up is obtained, therefore, when there is a minimum of distance between the microphone and the sound source. Depending on the service for which they are designed, microphones have little or great sensitivity as this distance is increased. Also depending on the service requirements, microphones may be designed to pick up sounds uniformly from all directions, from the front primarily. or from several angles. The physical shape of the microphone is determined by its use; some types are designed to be hand held, some to be mounted on floor or table stands or suspended from booms or cables, and some to be fixed in the correct operating position so that the operator has his hands free.

(2) The output of a microphone may be high impedance or low impedance, and microphones frequently are classified in these terms. The principle on which the microphone is constructed determines its output impedance; the low-impedance group includes carbon, dynamic, and velocity types; high impedance microphones include the crystal and capacitor types. Maximum output is obtained from a microphone when its impedance is matched to that of the load to which it supplies voltage. The turns ratio of the transformer which connects the microphone to an a-f amplifier must be such that the load reflected into its primary by the loaded secondary is equal to the impedance of the microphone.

b. Carbon Microphone.

(1) Operation of the most widely used microphone in military service, the *single button carbon microphone* (A of fig. 119), is based on the varying resistance of a pile of carbon granules as the pressure on the pile is varied. The insulated cup, called the *button*, which holds the loosely piled granules, is so mounted that it is in constant contact with the thin metal diaphragm shown in the illustration.

(2) Sound waves striking the diaphragm set up vibrations which vary the pressure on the button, and thus vary the pressure on the pile of carbon granules. The d-c resistance of the carbon granule pile is varied by this pressure in accordance with the vibrations on the diaphragm. The varying resistance is in series with a battery and the primary of microphone transformer *T*. The changing resistance of the carbon granule pile produces a corresponding change in the current of the circuit. The resulting pulsating direct

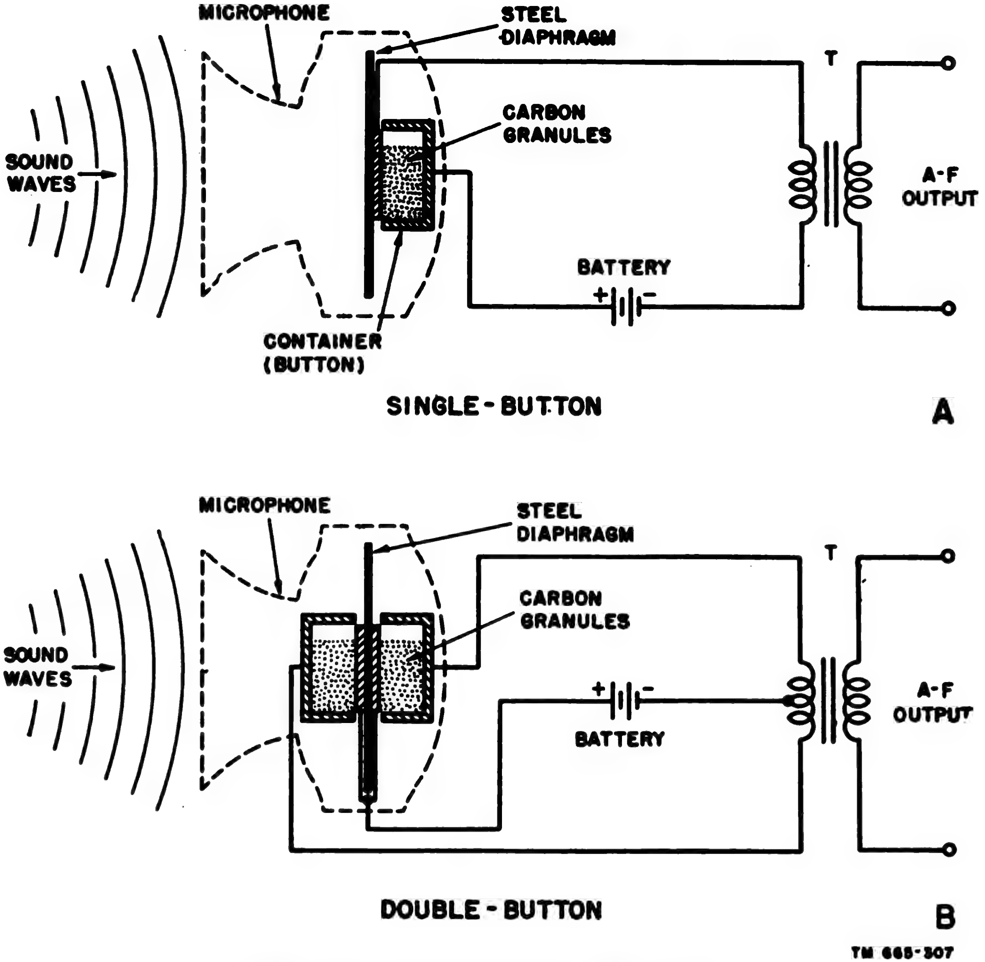

Figure 119. Carbon microphone and circuit.

current in the primary of *T* produces an alternating voltage in the secondary circuit. Transformer *T* has two functions: It steps up the voltage while matching the low impedance microphone to the much higher impedance of the grid circuit of the first a-f amplifier. A good single button microphone will develop as high as 25 volts peak in the secondary of the transformer, whereas battery voltages range from 1.5 to 6 volts and currents from 10 to 100 milliamperes, depending on the design of the microphone. The impedance of the microphone is usually from 50 to 200 ohms.

(3) Some microphones have two buttons, one on each side of the diaphragm. These are *double button carbon microphones* (B of fig. 119). They are so constructed that when the diaphragm presses on one button, it relieves the pressure on the other. The buttons are connected to the ends of a center-tapped primary of a microphone transformer. The push-pull arrangement cancels even harmonics and minimizes distortion. The double-button microphone seldom is used. It has been replaced by other types which are more suitable from the standpoint of frequency response and trouble-free operation.

(4) A disadvantage of carbon microphones is that the random changes in resistance between individual carbon granules produce a constant hiss which masks weak sounds. Another disadvantage is that the carbon granules stick to each other or pack when they are subjected to excessive currents or pressure. Packing reduces the sensitivity of the microphone and lowers the output while producing serious distortion. This can be remedied sometimes by tapping the case of the

microphone. A further disadvantage of carbon microphones is that the frequency response is limited by mechanical resonance in the diaphragm. The response can be increased by stretching the diaphragm, but this decreases the over-all output, so that there is usually a compromise between frequency response and output.

(5) Despite these disadvantages, the single button carbon microphone has advantages which warrant its use in many military applications. It is the only microphone which is also an amplifier in that its electrical power output is greater than the mechanical power required to vibrate its diaphragm. It is lightweight, rugged, and can be designed for extremely high output when its frequency response is limited to those frequencies which contribute most to intelligibility.

c. *Crystal Microphone.*

(1) The *crystal microphone* operates on the principle that Rochelle salt, quartz, or other crystalline materials exhibit a characteristic called the *piezoelectric effect.* These materials generate a voltage when mechanical stress is applied to the crystal. Since Rochelle salt has greater voltage output than other piezoelectric materials, it is most frequently used in microphones. If a Rochelle salt crystal has a metal foil on both surfaces, a voltage is developed between the foils when the crystal is vibrated or stressed in any manner.

(2) The basic crystal microphone unit, sometimes called a *bimorph cell,* is made by clamping two thin crystal slabs together after a thin metal foil has been cemented to the surfaces of each. A lightweight diaphragm is coupled to the cell. Its vibrations are transmitted to the cell in such a way as to cause twisting of the crystal, and thus the generation of voltage between the foil terminals. The voltage output is comparatively high but the frequency response is limited because of the stiffness and inertia of the diaphragm.

(3) A superior type of crystal microphone is known as a *sound cell* or *grill type* microphone (fig. 120). A number of bimorph cells are connected in series or series parallel for greater sensitivity. Sound falls on the crystal plates and vibrates them directly. A diaphragm is not used. Bimorph cells *A* are mounted in a bakelite framework, *B*, and the assembly is covered with a flexible airtight and moistureproof covering, *C*, which permits the cells to vibrate freely with variations in sound pressure. When the entire unit is excited by sound waves, the voltages are in phase and are proportional to the sound pressure. If the unit is subjected to mechanical shock or vibration, the resultant voltages are out of phase and no output is generated as the result of these disturbances.

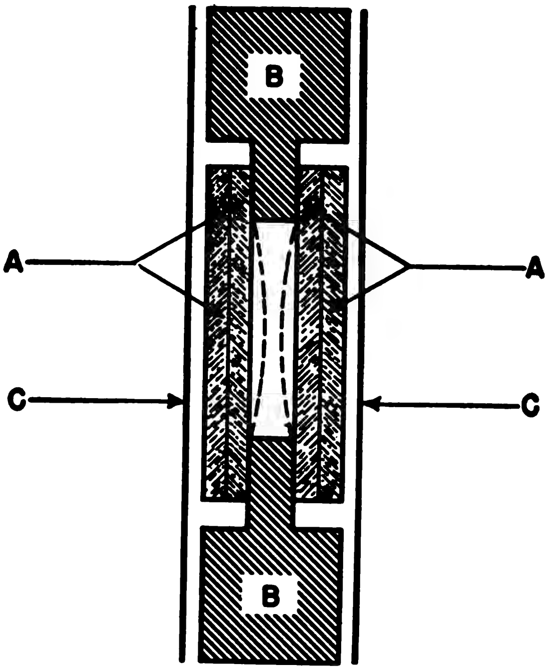

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Figure 120. Construction of crystal microphone unit.

(4) A crystal microphone has a high impedance and does not require an external voltage or current, and, therefore, it can be connected directly into the input circuit of a high gain a-f amplifier. Because its output is low, several stages of high gain amplification are required. Crystal microphones are delicate and and

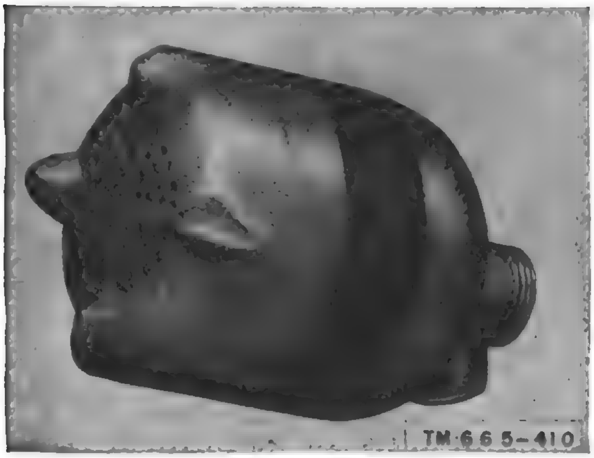

Figure 121. Military microphone.

fragile and must be handled with considerable care. Since exposure to high temperatures (above about 125°F.) may permanently damage the crystal unit, crystal microphones should never be exposed to the direct rays of the sun or the heat from radiators, or be operated close to high wattage electric lamps. The crystals are soluble in water and many other liquids, and precautions must be taken to protect them from prolonged exposure to moisture or excessive humidity. A typical military microphone is shown in figure 121.

d. Dynamic Microphone.

(1) The construction of a *dynamic microphone,* also called a *moving coil microphone,* is shown in figure 122. A coil of fine wire is fastened rigidly to the back of a diaphragm so that it is suspended in the field of a strong permanent magnet. When sound waves vibrate the diaphragm, this coil moves back and forth, cutting the magnetic lines of force of the permanent magnet at an audio rate; this induces in the coil a voltage which is the electrical representation of the sound waves.

(2) The sensitivity of a dynamic microphone (fig. 123) is higher than that of all other except carbon types. This microphone is comparatively light in weight and requires no external voltage. It is rugged and practically immune to effects of mechanical vibration, temperature, and moisture. Voltage output can be made independent of frequency over a wide range. A typical broadcast type dynamic microphone has a reasonably uniform response from 40 to 15,000 cps. A similiar microphone designed for communication circuits has a response of 100 to 6,000 cps. The average dynamic microphone has an impedance of 50, 100, 250, or 500 ohms

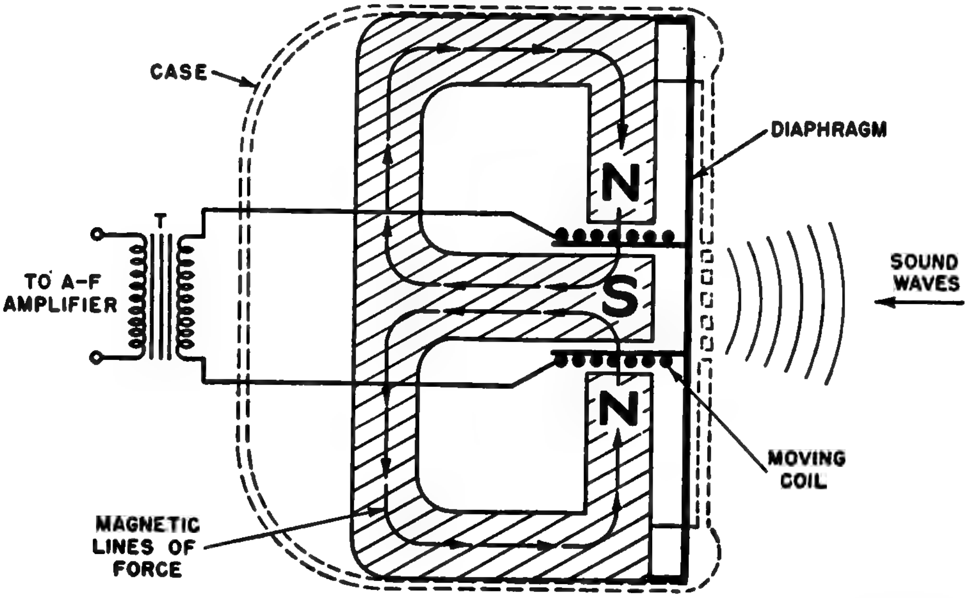

Figure 122. Construction of dynamic microphone and matching transformer circuit connections.

and, therefore, requires a transformer for matching it to the input of an a-f amplifier (T, fig. 122). Some units have a built-in transformer which permits them to be used with amplifiers having high impedance inputs.

e. Velocity Microphone.

(1) A variation of the dynamic microphone, the *velocity microphone* has a thin, lightweight, flexible, corrugated, metallic strip suspended between the poles of a permanent magnet (fig. 124). Sound waves cause the corrugated strip to vibrate in the magnetic field produced by the magnet. It cuts the lines of force of the magnet, and voltage is induced in it which is proportional to the frequency and strength of the sound waves. The force exerted on the strip is proportional to the velocity of the sound waves, which is the reason for its name. Because the corrugated conductor resembles a ribbon, a velocity microphone often is called a *ribbon microphone.*

Figure 123. Dynamic microphone and cable.

(2) The velocity microphone has a good frequency response. It responds only to those sounds originating directly in front of it. The ribbon is so fragile that this type of microphone is difficult to use in drafts or outdoors where wind pressure may be sufficient to create considerable background noise. Because the resistance of the ribbon is less than 1 ohm, a velocity microphone usually has a built-in transformer which raises its impedance to 250 or 500 ohms. The voltage output is so low that leads between the microphone and amplifier must be shielded carefully to avoid hum pick-up. Velocity microphones are used in some broadcast stations and with some public address systems, but rarely with field equipment.

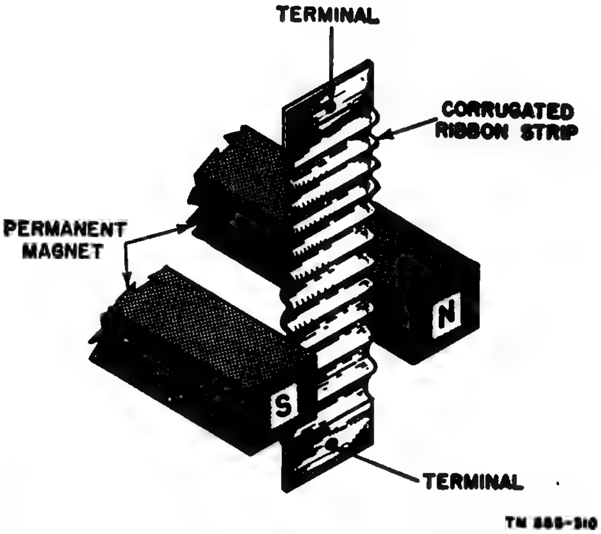

Figure 124. Construction of velocity microphone.

f. Condenser Microphone.

(1) *The condenser microphone* (A of fig. 125), so-named because it resembles a two-plate capacitor, consists of a movable metal diaphragm mounted close to but insulated from a heavier metal back plate. Vibration of the diaphragm caused by sound waves results in variations in the gap between the diaphragm and the back plate and thus changes the capacitance. When a d-c voltage is applied to the plates through a high resistance, *R*1, as in B, changes in capacitance cause a similar change in the current which flows through *R*1. This voltage is fed to the grid of the first a-f amplifier tube through coupling capacitor *C*1. *R*2 is the usual grid resistor for the amplifier.

(2) The condenser microphone has a high impedance. Its frequency response is good but the output is very low. The frequency response and the output voltage are affected by the capacitance of

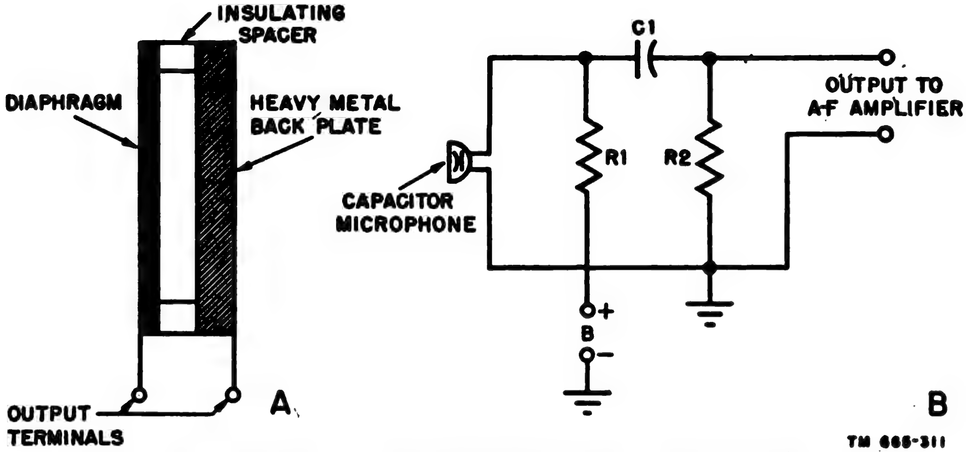

Figure 125. Construction of capacitor microphone and circuit.

the cable connecting it to the input of the amplifier. Usually, therefore, to compensate for losses in the connecting cable, at least one stage of a-f amplification is built into the microphone case. If this amplifier is self-powered, space must be provided for batteries; if it receives its operating voltages from an outside source, the connecting cable must have several additional conductors and is correspondingly bulkier. Condenser microphones seldom are used in radio or public address work, but they have some utility in certain types of sound measuring equipment.

g. Contact Microphone. The *contact microphone* responds to vibrations transmitted by contact with a solid rather than a fluid medium as in the case of the air pressure actuated microphone. It is used in areas where the background noise level is exceedingly high, as in tanks and aircraft. Examples are throat and lip microphones, which are strapped to these parts of the body and pick up vibrations directly from the throat and lip, respectively. Most contact microphones are crystal types, although they can be constructed around carbon button and dynamic units.

79. Speech Amplifiers

a. Purpose. A speech amplifier is needed in a radiotelephone transmitter whenever the output of the microphone is lower than the signal voltage required to drive the modulator tube. Therefore, the speech amplifier is considered to include all a-f amplifier stages between the microphone and the input of the stage whose output actually modulates the r-f carrier. When a class B modulator stage is used, the speech amplifier must include a power amplifier to supply power to the class B amplifier grids. The power amplifier that precedes the modulator is called the *driver* or *driver stage.*

b. Classes of Operation—Coupling. Audio amplifier circuits are designed to deliver *either* as much power or as much voltage as possible into a load impedance. When a large power output is the objective, the stage can be operated class A, class AB, or class B. When voltage gain is the objective, amplifiers usually are operated class A, because this class of operation is comparatively free from distortion. High voltage gain with minimum distortion is an important factor in the design of low level stages in a speech amplifier. Audio amplifiers commonly are classified according to the method of interstage coupling used; *resistance capacitance coupled*, *impedance coupled*, and *transformer coupled* amplifiers are a few examples.

c. Amplification Required in Speech Amplifier.

(1) The speech amplifier must supply a peak voltage equal to the value of d-c bias on the grid of the last class A amplifier if it is a single ended stage, and twice the d-c bias if the last stage is operated in push-pull. The *voltage gain* of an amplifier is the product of the voltage gain of each stage of the amplifier, including their interstage coupling networks. The approximate voltage gain of each stage is equal to E_{out}/E_{in}, where E_{out} is the peak a-c voltage appearing at the output of the stage and E_{in} is the peak a-c voltage appearing at the input of the stage.

(2) In actual practice, the speech amplifier must provide from 25 to 1,000 percent more voltage gain than needed to meet the requirements at the grid of the last a-f speech amplifier. This added gain compensates for circuit losses, deterioration of tubes, minor deviations in the values of circuit components and reductions in operating voltages. An audio gain control, similar to the volume control on a radio receiver, is used to adjust the output to the required level.

d. Class A Voltage Amplifiers. Class A amplifiers develop an output waveshape which is an amplified and faithful reproducton (for all practical purposes) of the input waveshape. In the interest of fidelity, the excitation voltage should never be large enough to drive the grid positive in respect to the cathode. Neither should it be large enough to drive the grid so far negative in respect to the cathode as to cause plate-current cut-off.

(1) *Resistance capacitance-coupled amplifiers.*

(*a*) In the circuit of a typical resistance capacitance-coupled triode voltage amplifier shown in A of figure 126, the voltage gain, *VG*, is equal to

$$VG=\frac{E_{out}}{E_{in}}=\mu\frac{R_1}{R_1+R_P}$$

where

E_{out} is the voltage appearing across the grid resistor R_g, of $V2$,

E_{in} is the voltage from grid to ground of $V1$,

r_p is the a-c plate resistance of $V1$,

R_1 is the equivalent load resistance of $V1$,

μ is the amplification factor of $V1$.

(*b*) In the typical resistance capacitance-coupled pentode voltage amplifier, in B, the voltage gain, *VG*, is equal to

$$VG=\frac{E_{out}}{E_{in}}=Gm\times R_{eq}$$

where

G_m is the mutual conductance of $V1$ and R_{eq} is the equivalent resistance of r_p, R_c, and R_g in parallel.

The value of R_{eq} can be found from the formula

$$R_{eq}=\frac{1}{\frac{1}{r_p}+\frac{1}{R_c}+\frac{1}{R_g}}.$$

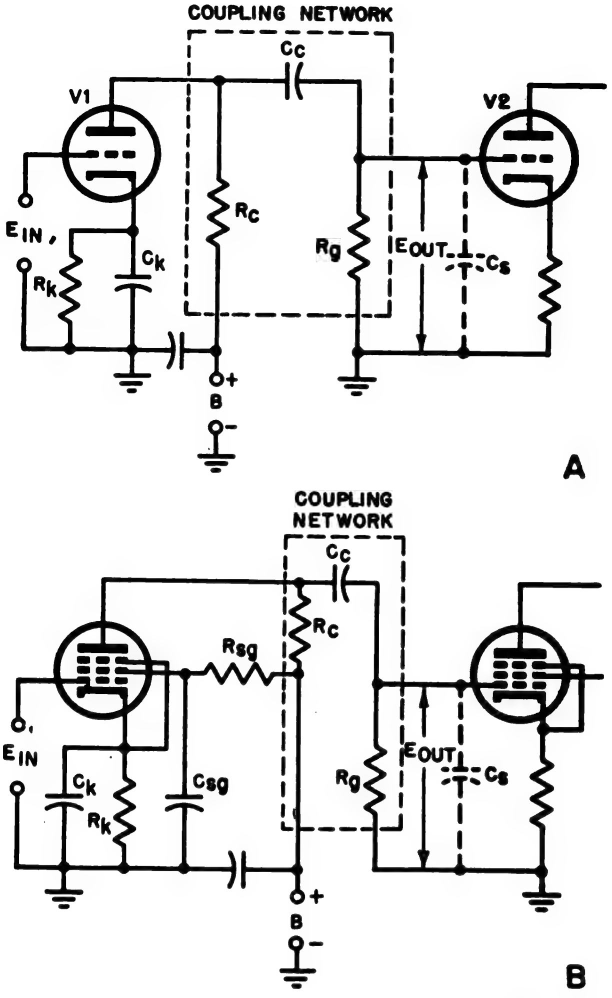

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Figure 126. Resistance capacitance coupling using triodes and pentodes.

The voltage gain of a resistance capacitance coupled amplifier, as determined by the formulas above, is correct for only the middle portion of the bandpass where the gain is considered to be fairly uniform or flat. The reduction in voltage gain begins to be noticeable when the frequency is higher or lower than two critical frequencies.

(*c*) The low-frequency response of a resistance capacitance-coupled amplifier, or simply a ***resistance-coupled amplifier***, is determined mainly by the time constant consisting of C_c and R_g. The time constant of these components must be long as compared with the lowest audio input frequency to *V1*. To an extent, C_k also determines the low-frequency response. Its capacitive value must be large to obtain a very low reactance at the low frequencies. The larger the value of C_k, the better the low-frequency response. C_s (fig. 126) is one factor that determines the high-frequency response of a resistance-coupled amplifier. C_s is an imaginary capacitor existing from grid to ground of $V2$. This imaginary capacitor represents the input capacitance of tube $V2$ in figure 126, and has a value which is partly proportional to the voltage amplification of the tube. For triodes, C_s can become large, approximately 15 to 40 micromicrofarads, or even more in the case of high gain tubes. For tetrodes, largely because of the minute value of grid-to-plate capacitance (approximately .005 micromicrofarads) the input capacitance is much smaller than for a triode. It is still, however, appreciable, and may be approximately 5 to 10 micromicrofarads. C_s may be made effectively smaller in value so that it presents a higher reactance at the higher frequencies, thus improving the high-frequency response. This is accomplished by using tetrodes and pentodes (lower interelectrode capacitance) instead of triodes as the resistance-coupled amplifier tubes, making the connecting leads of the associated circuit components as short as possible, and by proper placement of circuit components on the amplifier chassis. Lowering the value of R_c also improves the high-frequency response, since it reduces the effects of C_s which is effectively in parallel with it. R_c cannot be made too small in value because the voltage gain of the resistance-coupled amplifier becomes very small. The selection of R_c as a load resistor depends on whether a greater voltage gain or a better frequency response is desired.

(2) *Transformer-coupled stages.*

(*a*) In figure 127, which shows a *transformer-coupled* amplifier, the plate of $V1$ is coupled to an inductive load, the primary of coupling transformer $T1$. The secondary of $T1$ is coupled to the grid of the following tube, $V2$. Coupling transformer $T1$ can have any desired degree of voltage step-up or step-down between its primary and secondary windings. Transformer coupling can be used between single-ended stages as shown, between a single-ended and a push-pull stage, or between two push-pull stages.

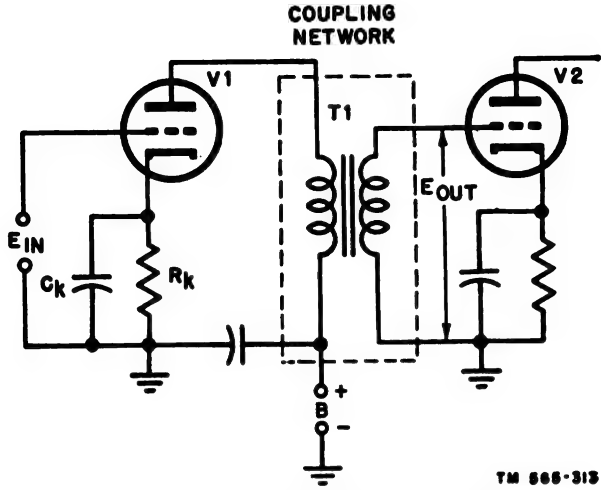

Figure 127. Transformer coupling using triodes.

(*b*) The voltage gain of a transformer-coupled stage in the middle portion of the amplifier bandpass is equal to E_{out}/E_{in}, which is equal to μN where μ is the amplification factor of $V1$ and N is the turns ratio of coupling transformer $T1$. As in resistance-coupled amplifiers, the circuit components cause a reduction in gain which becomes appreciable at the high and low frequencies. A transformer consists of resistance, capacitance, and inductance, the values of which affect the voltage gain of the transformer-coupled stage at all frequencies.

(*c*) The response characteristic of a resistance-coupled amplifier is usually more uniform over a wider frequency range than a transformer-coupled amplifier. As with the resistance-coupled amplifier, the response characteristic drops off rapidly as the frequency is decreased because the reactance of the primary inductance of $T1$ decreases with frequency. The result is a decrease in the output voltage gain. In the high-frequency range, the frequency response drops off also as the frequency is increased because the distributed capacitance between the winding of the secondary of $T1$ produces a low reactance path for the input signal frequencies. This results also in a decrease in the output voltage gain.

(*d*) Transformer coupling seldom is used when pentodes or tetrodes serve as the amplifier tubes, because it is extremely difficult to design a transformer which presents a high enough load impedance to the tetrode or pentode tube. The use of transformer coupling in pentode plate circuits generally results in poor gain and considerable reduction in low-frequency response.

(3) *Phase inverter* (fig. 128).

(*a*) Push-pull stages often are used in a speech amplifier. Such stages may be needed to supply adequate voltage to drive an a-f output stage; in addition, operation of tubes in push-pull reduces second harmonic distortion. The voltages applied to the push-pull grids must be equal in amplitude and 180° out of phase in respect to each other. The simplest method of obtaining equal voltages 180° out of phase is to use a coupling transformer having a split secondary winding. This method is efficient, but it is not always possible to get a transformer having the desired frequency response characteristics. The alternate method of developing the proper voltages for the push-pull grids is to use an electronic circuit called a *phase inverter.*

(*b*) In figure 128, A is a *cathode loaded* phase inverter. The load voltage is developed across two equal load resistors, R_{Lp} and R_{Lk}. Resistor R_{Lp} is placed in the plate circuit of $V1$ and feeds the grid of tube $V2$. Resistor R_{Lk} is placed in the cathode circuit of $V1$ and feeds the grid of tube $V3$. The voltages across R_{Lp} and R_{Lk} are equal in magnitude since R_{Lp} equals R_{Lk} and the same tube current flows through both of them. These voltages are 180° out of phase with each other because the plate load voltage is 180° out of phase with the grid voltage, and the cathode load voltage is in phase with the grid voltage. This is true since an increase in grid voltage increases the plate current. An increase in plate current decreases the plate voltage which decreases the voltage across the plate load resistor, R_{Lp}. The increase in plate current increases the voltage across the cathode load resistor, R_{Lk}. Consequently, as the voltage on the grid increases, the voltage across R_{Lp} decreases and the voltage across R_{Lk} increases. The voltage appearing at the grids of $V2$ and $V3$ are then 180° out of phase with each other. The a-f output consists of two voltages 180° out of phase with each other and of equal magnitude.

(*c*) In the *tapped output* phase inverter, in B, two tubes, $V1$ and $V2$, provide the proper phase inversion and amplification. $V1$ and $V2$ are identical triodes or separate halves of a dual triode. The output of $V1$ is fed to the grid of $V3$, and the output of $V2$ is fed to the grid of $V4$. The output voltage of $V1$ appears across resistors $R3$ and $R4$ in series which constitute the total grid-leak resistance of $V3$. This voltage is 180° out of phase with the input of $V1$. The grid of $V2$ is tapped onto the junction of $R3$ and $R4$; the voltage on the grid of $V2$ is therefore in phase with the voltage at the plate of $V1$, and the output voltage of $V2$ is 180° out of phase with the output of $V1$. Consequently, the voltages at the grids of $V3$ and $V4$ are 180° out of phase with each other. Proper values for the resistors used in this circuit enable the a-f output to have two voltages, equal in magnitude.

(*d*) Natural variations in the characteristics of tubes make it nearly impossible for two tubes to have identical characteristics. The *self-balancing* phase inverter, in C, is used to eliminate the need for precise values of

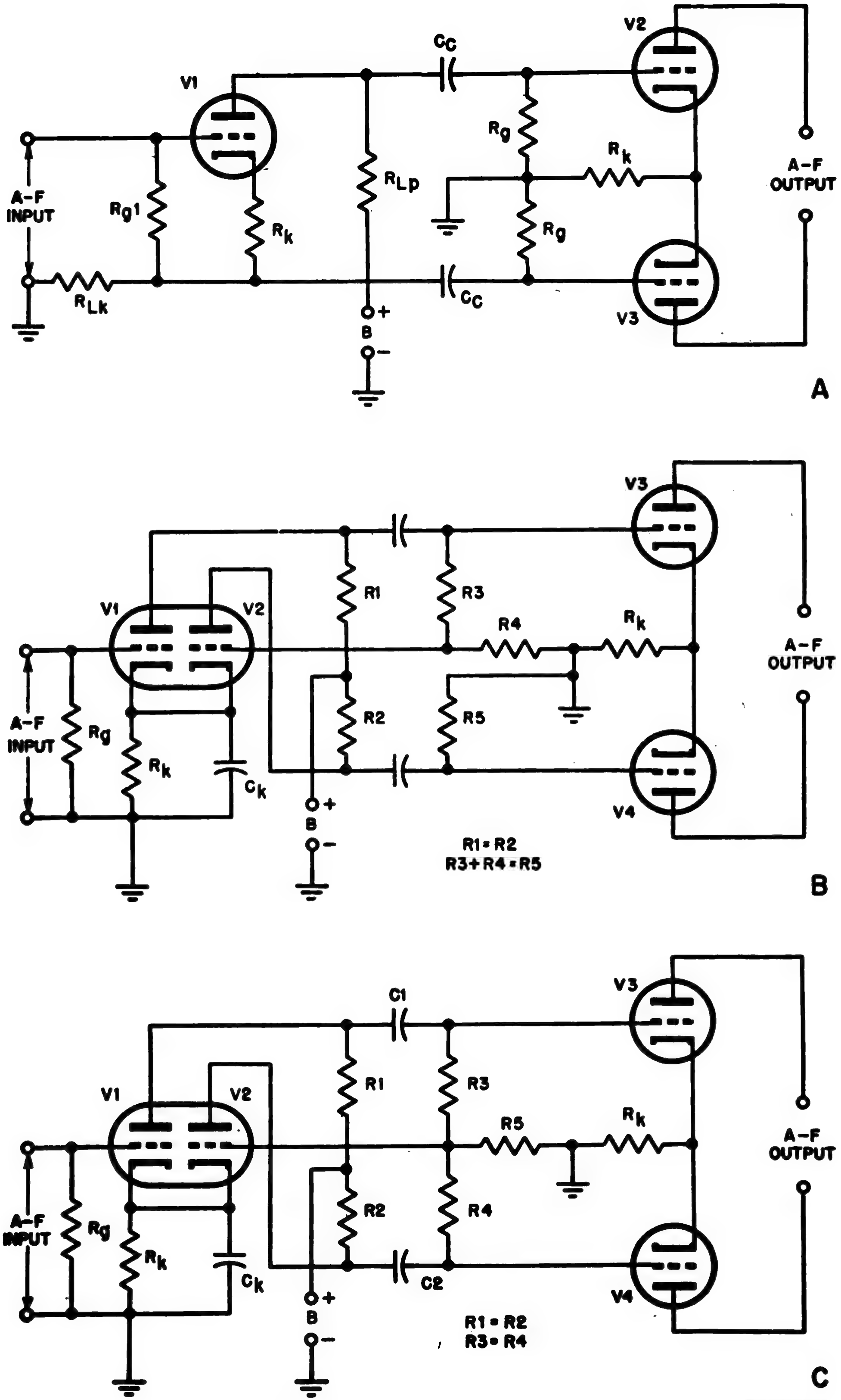

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Figure 128. Various types of phase inverter circuits.

components. The *V*1 output voltage appears across *R*3 and *R*5 in series. The voltage drop across *R*5 is applied to the grid of *V*2, and the output voltage of *V*2 appears across *R*4 and *R*5 in series. The voltage across *R*3 is 180° out of phase with the voltage across *R*4 for reasons explained in the preceding paragraph.

(*e*) The action of this circuit can best be understood by considering a typical set of values. Assume that the input to *V*1 is -1 volt and the output is $+10$ volts. For proper operation, the output of *V*2 should be -10 volts and the input to *V*2 should be $+1$ volt. This voltage is obtained in the folowing manner: The voltage divider of *R*3 and *R*5 is so designed that 20 percent of the *V*1 output voltage exists across *R*5. The voltage divider of *R*4 and *R*5 is so designed that 10 percent of the output voltage exists across *R*5. Consequently, if the *V*1 output voltage is $+10$ volts, the resultant voltage across *R*5 is $+2$ volts. However, since the *V*2 output voltage is -10 volts, there is also a -1 volt across *R*5, and the net voltage across *R*5 is $+1$ volt, which is the desired voltage. This grid voltage provides an output of -10 volts, and the circuit is balanced properly.

(*f*) Assume now that there is an instantaneous unbalance in the circuit. If the output of *V*1 is $+11$ volts instead of $+10$ volts, then the following occurs. The voltage across *R*5 caused by the increase in the *V*1 voltage increases by .2 volt and contains across it a net value of $+1.2$ volts. This increases plate current *V*2, so that its output voltage tends to decrease toward -10 volts. The circuit therefore tends to balance itself.

(*g*) In a similar manner, if the output of *V*2 increases instantaneously to -11 volts, the voltage across *R*5 decreases and the output voltage tends to decrease toward -10 volts again. Actually, there is usually a slight difference in voltage or unbalance between the two grids. However, this circuit tends to prevent the unbalancing from becoming too great.

e. Modulator Driver Requirements.

(1) Since the relationship between instantaneous grid voltage and grid current in class B modulators is not linear, the grids present a varying impedance to the driver over the a-f excitation cycle. To avoid distortion in the modulator caused by the change in grid impedance, the modulator driver must supply a constant voltage to the modulator grids, regardless of the change in grid impedance. When a modulator driver meets these requirements, it is said to have good *voltage regulation.* The fundamental factor in achieving good voltage regulation is a low internal resistance to be obtained in the modulator driver stage. This means that the modulator driver tubes must have a low value of plate impedance. Low-mu triodes best satisfy this condition. Pentodes and tetrodes are not as satisfactory for this service, but they may be used if sufficient *inverse feedback* is used to lower the effective plate impedance.

(2) In order to obtain maximum power transfer from driver to modulator, it is necessary to match the higher driver plate impedance to the relatively low modulator input impedance. This is done by means of a driver transformer having the highest possible voltage step-down between its primary and secondary. In this case, the plate resistance of the driver tubes, as seen by the modulator grids, is comparatively high. Conversely, the modulator grid impedance is low, as seen by the driver plates.

(3) As explained previously, variations in the instantaneous class B grid voltage and current are not linear, and this results in variations in input impedance and possible distortion in the modulating signal. If high-mu triodes are used as class B modulators, they can be operated with very little or no d-c biasing voltage on their grids. This reduces the variation in grid impedance over the audio-frequency cycle, and consequently gives the driver a more constant input impedance load. Distortion therefore is reduced.

Tubes operated in this manner often are called *zero bias* tubes.

(4) The driver transformer may couple the modulator driver plates directly to the modulator grids. It may also be designed to work into a low impedance line (usually 250 or 500 ohms) so that the speech amplifier may be located some distance from the modulator stage. In this case, the modulator grids are fed by a line-to-grid transformer designed for class B service.

f. Driver Circuits.

(1) The circuit shown in A of figure 129 is the usual single ended class A triode amplifier stage used as the modulator driver. Transformer coupling, *T*1, is used from the preceding speech amplifier stage, and transformer coupling, *T*2, is used similarly to couple the modulator driver to the following class B modulator. R_k is the normal cathode biasing resistor and C_k is the cathode bypass capacitor.

(2) The circuit in *B* is a push-pull driver fed by a tapped output phase inverter, *V*1 and *V*2. R_k and C_k are the cathode biasing resistor and cathode bypass capacitor, respectively. Other components function as explained in the description of the tapped output phase inverter.

(3) In some applications it is necessary to use pentode tubes, operating class AB as the modulator driver. Since the pentode normally has a high plate impedance, and since a low driver plate impedance is necessary, as explained previously, negative feedback or inverse feedback circuits are used, as in C. In this circuit, part of the plate voltage of each modulator driver stage is fed back to its grid through the voltage dividing networks, *R*1–*R*2 and *R*3–*R*4. *C*1 and *C*2 are d-c blocking capacitors. The feedback voltage is 180° out of phase with the voltage applied to the grids through the transformer secondary of *T*1. This, in effect, decreases the grid voltage and reduces the plate impedance of the modulator driver tubes. The percentage of feedback increases as *R*2, or *R*4, is made greater, since a greater voltage drop appears across it. As the percentage of feedback is increased, the impedance of the driver tubes is decreased. However, *V*1 must supply a higher signal voltage for a given output voltage. The percentage of feedback, therefore, cannot be made too large, as this would result in *V*1 being unable to supply the required voltage without distortion.

80. Modulator Stage

Triodes, pentodes, and beam power tubes are used in the modulator stage to provide the audio power necessary to modulate the r-f modulated amplifier. The modulator may use one tube, two or more tubes in parallel, two tubes in push-pull, or any even number of tubes in push-pull parallel. All classes of operation are used. Distortion, plate circuit efficiency, and power output are lowest for class A operation; both of these factors increase for class AB1, class AB2, and class B operation in that order. The type of circuit connection and class of operation depends on the required power output, permissible distortion, and on the plate voltage and current available from the power supply.

a. Class A Modulator.

(1) Class A modulators can be operated with comparatively low distortion. However, they also have a relatively low plate efficiency and consequently a low power output. For this reason, the output of a single tube class A modulator frequently is not great enough to modulate the r-f amplifier. To obtain increased power it is necessary to operate two, or more, of these tubes in parallel, push-pull, or parallel push-pull. In a parallel connected stage, both power output and d-c power input are increased.

(2) Power output in the class A modulator can be doubled, harmonics and hum caused by variations in plate supply voltage can be minimized or decidedly reduced, and the plate load resistance halved by connecting two tubes in push-pull. Distortion in a push-pull stage is considerably less than that for single tube operation. Appreciably more than twice the single tube output can be obtained by making the plate-to-plate load resistance approach the plate load resistance speci-

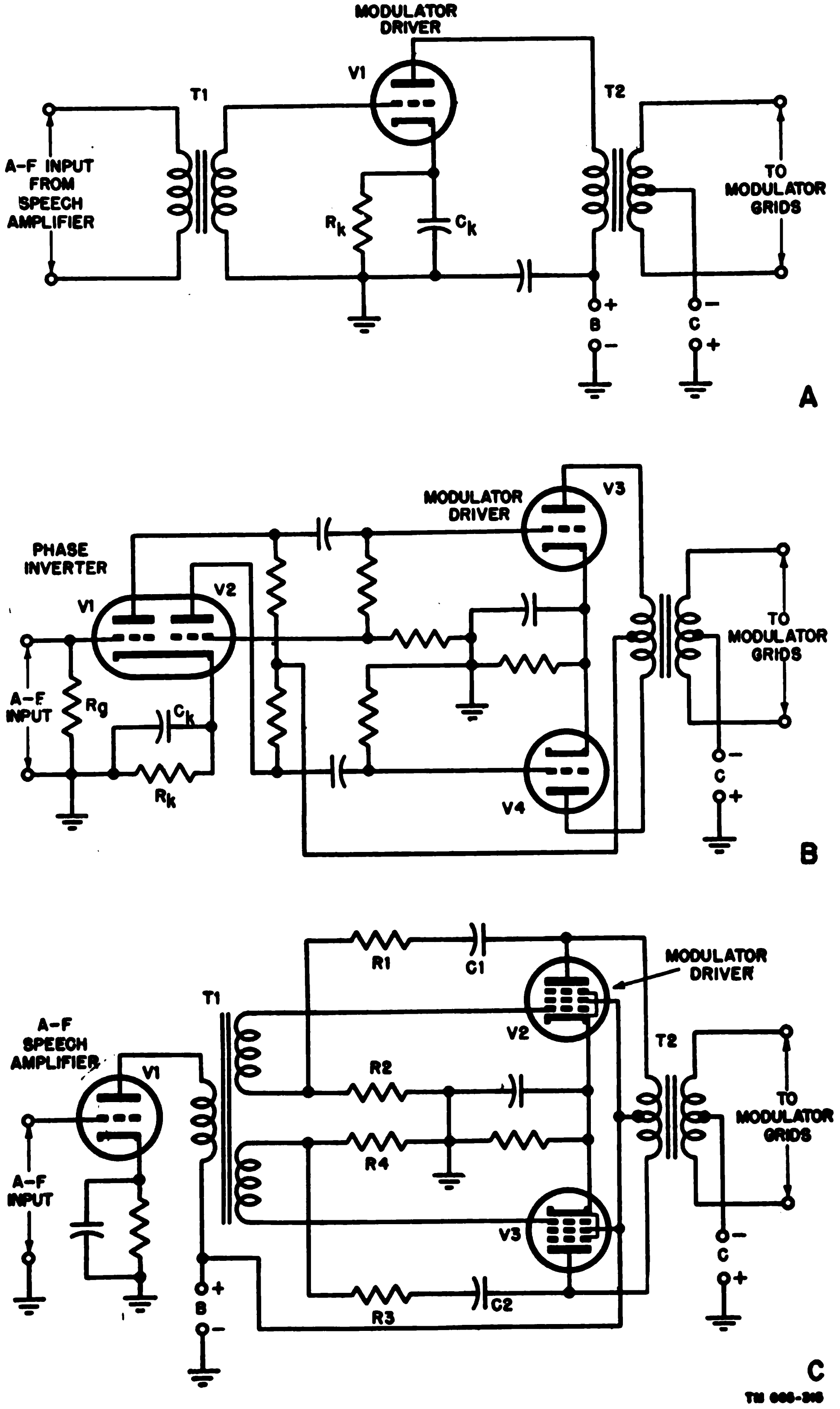

Figure 129. Various types of modulator driver circuits.

fied for a single tube. The grid bias for a push-pull class A modulator can vary from the value specified for a single tube to one-half the bias voltage which would produce plate-current cut-off at a plate voltage about 1.4 times the operating plate voltage. The peak-to-peak input signal voltage is twice that of the d-c bias voltage.

b. Class AB and Class B Modulators. Class AB and class B a-f amplifiers are always operated in push-pull to minimize distortion. In class AB1 operation, the bias voltage is about 40 percent greater than that for class A operation. The bias voltage is nearer the bottom of the straight portion of the i_p–e_g characteristic curve and therefore the power output, distortion, and efficiency are greater than for class A operation. The peak a-f grid voltage applied to each tube is slightly less than or equal to the d-c bias.

c. Class AB2 Operation. In class AB2 operation, the peak grid voltage applied to each tube is always greater than the grid bias. Grid current flows for more than one-half but considerably less than the full excitation cycle. The grid current flow represents a power loss which, when added to the loss in the driver transformer, equals the minimum power that must be supplied by the driver stage. Bias for a class AB2 stage must be supplied from a source having good regulation. The usual procedure is to use a separate well regulated bias supply. Tetrodes, pentodes, and beam power tubes generally are used in class AB2 modulators, because their higher power sensitivity makes it unnecessary to use a large modulator driver stage.

d. Class B Modulators.

(1) Class B audio amplifiers always are operated in push-pull. The tubes are biased so that the plate current is zero or almost zero when no a-f signal voltage is applied. Consequently, plate current flows in each tube for approximately one-half of each excitation cycle. Tetrodes operated with screen and control grids connected to each other (so that the tube operates as a triode) often are used as class B modulators. Tetrodes and beam power tubes operated in this manner have a high amplification factor because the grid potential acts on the electron stream over a considerable portion of the space between cathode and plate. The grid structure is such that grid current is not excessive, even when the grids are driven highly positive. Triodes having a high amplification factor or mu also are used as class B modulators. These triodes and tetrodes (connected as described above) require little or no bias. The high amplification factor results in low plate current, even with no bias.

(2) The bias voltage for class B modulators or a-f amplifiers must be obtained from a source having a low internal resistance. Batteries often are used when the bias voltage needed is relatively low. Unfortunately, the internal resistance of a battery increases with age, and it may become high enough to act as a grid-leak resistor so that the bias varies with the a-f excitation voltage. The changing bias produces distortion. Therefore, batteries should be replaced when excitation produces approximately a 10-percent change in bias voltage. If the bias is supplied from a separate power supply, the bleeder current should be at least 10 times the peak grid current.

(3) Class B modulators must not be operated without the specified load on the secondary of the modulation transformer. The plate voltage must not be applied until the modulated r-f stage is drawing the current which reflects the required load to the modulator plates. If the secondary is unloaded or operated with a load considerably lower than normal, the primary impedance rises abruptly and causes the a-f voltage across it to be excessive. This unusually high voltage is likely to break down the insulation and damage the modulation transformer. When testing a modulator alone, always load the secondary of the modulation transformer with a resistor equal to its output impedance and having a wattage rating equal to or greater than the power output of the modulator.

e. Modulator Circuits.

(1) When the modulator power requirements are low as in low power plate modulated transmitters or in higher-power grid, screen, suppressor, or cathode modulated transmitters, a class A modulator

can be used. The circuit of a class A modulator is the same as that of either of the class A drivers shown in A and B of figure 129. The grid of the modulator can be fed through an interstage transformer or resistance capacitance-coupling. The transformer in the plate circuit can be a modulation transformer or a plate-to-line transformer which matches the audio line to a second transformer which feeds the power into the modulated r-f amplifier load. Design factors for class A modulators are the same as those for class A drivers. The only difference is in the design of the coupling transformer in the plate circuit. A typical modulator chassis is shown in figure 130.

(2) The circuit of a class AB1 modulator is exactly like that of the class AB1 driver (C of fig. 129). Design factors are the same, and the only difference is that $T2$ must be a modulation transformer instead of a driver transformer.

(3) The circuit of a class B modulator is similar to that of any other push-pull audio amplifier. It differs from other classes of amplifiers only in the selection of the driver and modulation transformers and in the values of operating bias and plate voltage.

81. Speech Compression and Clipping

a. General.

(1) In ordinary communications, when the operator speaks evenly at a uniform distance from the microphone, an average volume range of speech is established. If he shouts or deliberately accentuates certain words, syllables, or phrases, or changes his distance from the microphone, the volume range increases. If the transmitter is set for 100-percent modulation on volume peaks, the average percentage of modulation is low and the communication range of the transmitter is reduced.

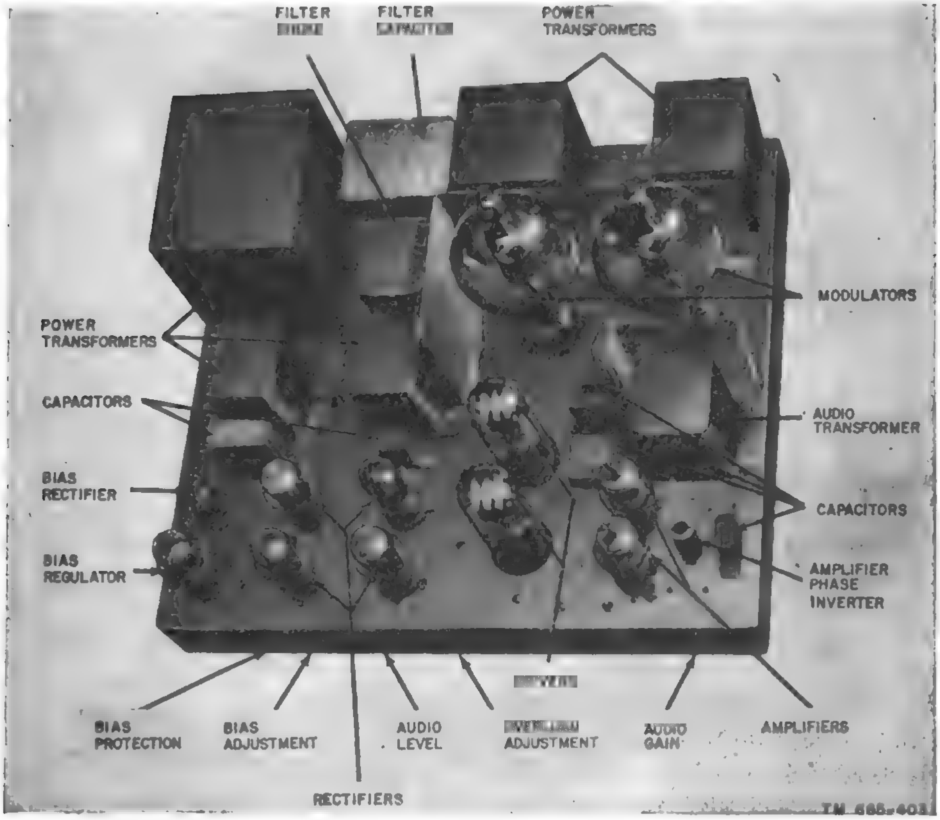

Figure 130. Typical modulator chassis.

(2) If the transmitter is adjusted for a higher average percentage of modulation, it is overmodulated on these volume peaks. The negative half of the modulation cycle is clipped because the plate of the modulated stage (when using plate modulation) is driven beyond tube cut-off. This clipping produces a modulated r-f wave which is high in harmonic content. The harmonics appear in the side bands and cause interference over a wide band of frequencies. A high average percentage of modulation with little or no danger of overmodulation is obtained through the use of *automatic modulation control* or *volume compression*. In this system, the gain of the a-f speech amplifier is constant until the input signal reaches a predetermined level. Above this point, the gain decreases rapidly as the signal voltage increases. A speech or volume compressor can be set so that the average modulation percentage is 80 to 90 percent, and volume peaks which are above the predetermined level are compressed to the point where they rarely exceed the level required for 100-percent modulation.

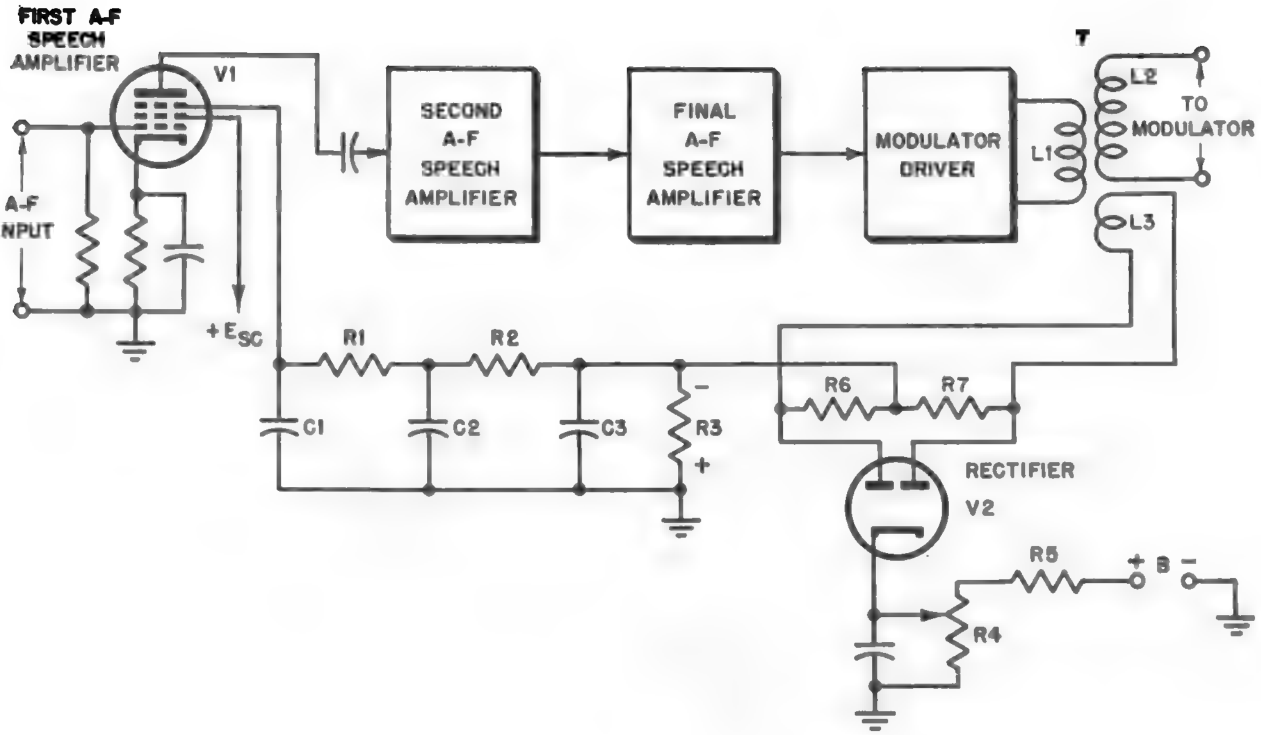

Figure 131. Volume compressor or automatic modulation control.

(3) *Speech clipping*, also called *speech limiting*, is a second method of obtaining a high percentage of modulation without overmodulating during volume peaks. This system clips or chops off the occasional high amplitude volume peaks so that their maximum amplitude is only equal to or slightly higher than that of the average voice peaks. Since the amplitude of the volume peaks determines the transmitter adjustments for 100-percent modulation, the gain of the speech amplifier can be increased until the average peaks produce nearly 100-percent modulation.

b. Volume Compressor Circuit.

(1) A basic volume compressor (fig. 131) consists of a rectifier which rectifies a portion of the voltage at the output of the modulator driver and develops a negative voltage which is used to bias the suppressor grid of the first a-f speech amplifier tube. A strong signal develops a large negative bias which reduces the

gain of the first a-f speech amplifier by making its suppressor grid more negative. The rectifier is biased so that it does not conduct until the input a-f signal reaches a level corresponding to 80- or 90-percent modulation.

(2) In the circuit illustrated, a portion of the a-f modulating voltage developed across the secondary winding, *L*3, of the driver transformer is applied to the plates of the full wave diode rectifier, *V*2. *V*2 conducts only during the positive half cycles of the a-f signal. The positive half cycles of a-f signal voltage are rectified to develop a negative voltage across *R*3, as shown. Since this resistor is in the suppressor grid return of the first a-f speech amplifier, *V*1, any negative voltage biases the suppressor and reduces the gain of *V*1. Consequently, positive peaks of a-f signal voltage which would ordinarily cause overmodulation are reduced in amplitude, preventing this condition. A positive voltage, called *advanced* or *delay bias*, is applied to the cathode of *V*2 through resistors *R*4 and *R*5, so that the tube does not conduct until the voltage on its plates is greater than that on its cathode. Consequently, if the delay bias is adjusted to equal the peak a-c voltage at the output of the modulator driver for 80-percent modulation, *V*2 will rectify and produce a biasing voltage whenever the signal exceeds this predetermined modulation level. The two 100,000-ohm resistors, *R*6 and *R*7, between the plates of *V*2 are used to balance the outputs from the separate halves of the rectifier. *R*1, *R*2, *C*1, *C*2, and *C*3 form a low pass filter which removes a-f variations from the output of the rectifier.

c. Speech Clipper Circuit (fig. 132).

(1) Speech clippers can be inserted between two stages in an a-f speech amplifier (*low level clipping*) as in A, or between the secondary of a modulation transformer and the B–plus line to the modulated r-f amplifier (*high level clipping*) as in B. A modulated waveform produced by a clipped wave looks much like that produced by overmodulation. It contains the same high order harmonics and wide side bands that cause interference to other stations. A *low pass filter* is used to reduce the harmonics. This usually is designed to pass only those frequencies needed for intelligible speech, and it attenuates or eliminates all others.

(2) In the low level speech clipper, in A, the clipper circuit, consisting of diodes *V*1 and *V*2 shunts the output of the second and the input of the third a-f amplifiers. *V*2 is so connected that it conducts on the positive half of the a-f signal voltage and *V*3 conducts on the negative half-cycles of a-f signal voltage. The diodes are biased by batteries BA1 and BA2 so that they do not conduct until the signal voltage exceeds the battery voltage. Consequently, if the bias voltages are made slightly more than the average value of the a-f peak signal voltage, *V*2 and *V*3 conduct and short circuit all higher than average peaks. The harmonics caused by clipping are removed by the low pass filter (shown in dotted lines) between the output of the third a-f amplifier and the following stage. Proper adjustment of the LEVEL CONTROL is an important factor in the operation of the low level clipper. This control must be set so that the transmitter cannot be overmodulated when speaking in a normal voice at a designated distance from the microphone.

(3) The high level clipper, in B, consists of a high voltage rectifier connected in series with the B-plus lead going to the modulated r-f amplifier. The rectifier tube is so connected that it conducts and supplies plate voltage to the modulated r-f amplifier at levels of modulation up to 100 percent. Above 100 percent, the negative modulated a-f peaks are greater than the d-c voltage; the rectifier therefore does not conduct and the d-c supply voltage on the modulated r-f amplifier drops to zero. This voltage cannot go in a negative direction as it would without the high level clipper. The function of the filter is the same as that shown in A.

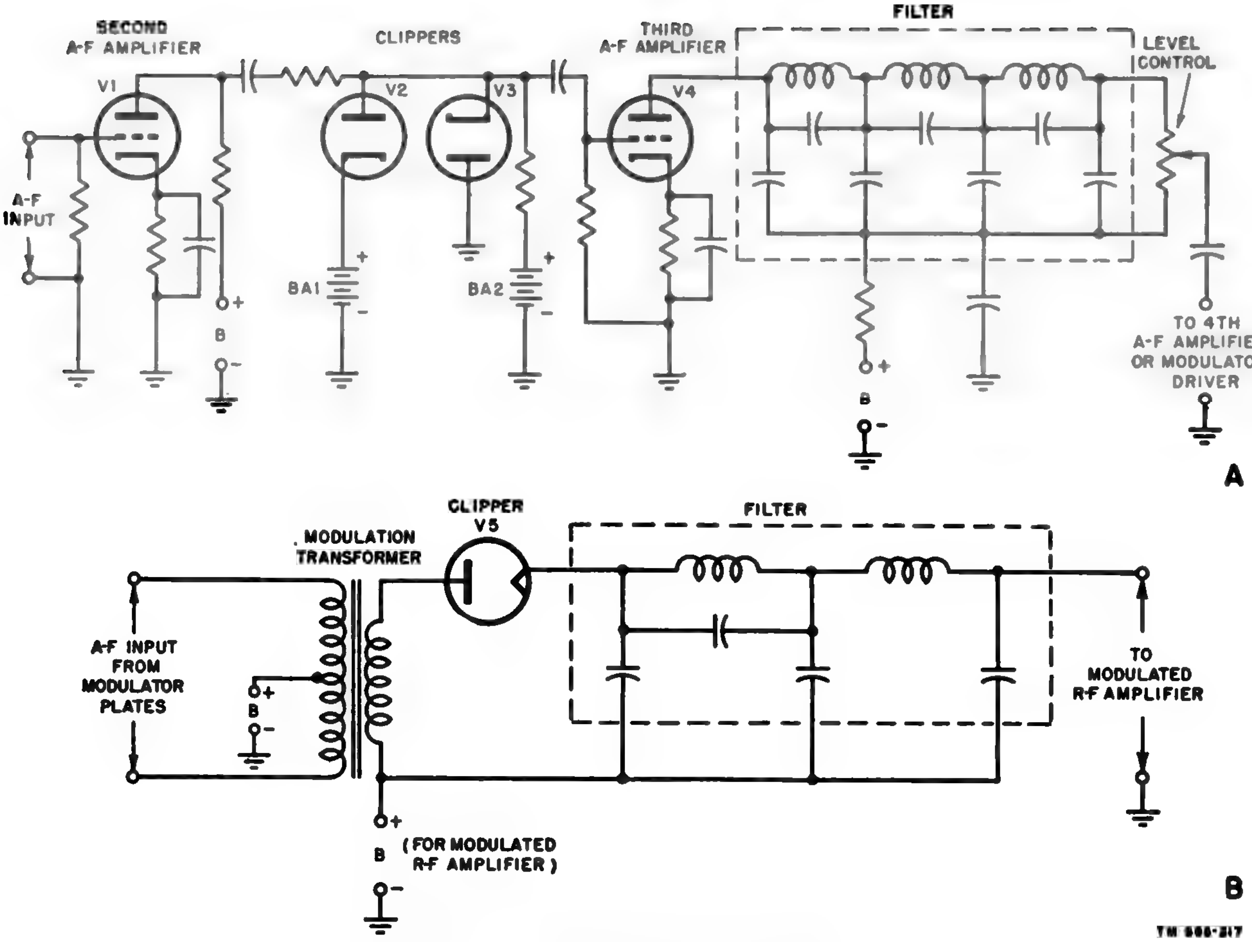

Figure 132. Low and high level speech clippers.

82. Tone Transmitters

a. When c-w telegraph signals are being received on a superheterodyne receiver, the unmodulated carrier is heterodyned with the output of a bfo (beat-frequency oscillator) in the receiver in order to obtain an audible beat. Under certain conditions, the transmitter or receiver, or both, may be so unstable as to cause the c-w signal to drift until the beat note between the carrier and bfo rises to the supersonic range. Under these conditions, copying may be difficult or contact may be lost. This trouble can be avoided by *tone transmission*—that is, by using a *tone modulated wave.*

b. In tone transmission, the carrier is modulated at a fixed audio rate between approximately 500 and 1,000 cps. A buzzer or an audio oscillator generally is used as the tone source. Since the tone source is constant, the modulation can be adjusted to exactly 100 percent. The tone source can be keyed simultaneously with the transmitter or it can be left in operation during the entire transmission. Tone modulation has a slightly greater effective range than voice transmission for the same transmitter output power. This is the case because static, interference, and weak signals may cause the loss of several words or phrases from voice transmission. The sharp keying of the tone modulated transmitter cuts through interference and is easier to copy under adverse conditions. The range of a tone modulated transmitter is less than that of a c-w transmitter of the same output power.

83. Low-Power-Modulated Radiotelephone-Telegraph Transmitter

a. R-F Circuits. A typical self-excited, low-power radiotelephone-telegraph transmitter is shown in figure 133. *V*1 is a Hartley oscillator with *L*1 and *C*1 as its tank circuit. The plate section, A, of *L*1 is connected between the plate and filament of *V*1 through *C*2, ground, and the center tap of the filament transformer, *T*5. The grid section, B, of *L*1 is connected between the grid and filament through *C*3, *C*2, ground, and the center tap on the secondary of *T*5. The circuit is biased by grid-leak resistor *R*5. *L*3 is an r-f choke which prevents r-f currents from entering the high voltage power supply and the keying circuits. The voltage developed across section C of *L*1 is applied to the grid of the r-f amplifier, *V*2. Interstage coupling capacitor *C*4 is tapped on *L*1 to minimize loading on the oscillator. The bias for *V*2 is developed by the total voltage drop across *R*1, *R*2, and *R*3 when code key *S* is closed, as shown. *L*4 serves as an r-f choke. Capacitors *C*5 and *C*11 bypass to ground any r-f currents which pass through r-f chokes *L*4 and *L*3, respectively. Variable capacitor *C*6 is the neutralizing capacitor for *V*2. Oscillation in the r-f amplifier can be prevented by adjusting *C*6 to cancel the out-of-phase voltages on the grids.

b. A-F Circuits. Sound waves striking the diaphragm of the microphone, *M*, cause audio-frequency currents to flow in the primary of *T*2 and induce an a-f voltage in its secondary. This voltage is applied to the grid of *V*3 which is the driver tube for class B modulator tubes *V*4 and *V*5. Bias voltages for the driver and modulator are taken from potentiometers *R*3 and *R*2, respectively. Note that these stages normally are biased by the voltage developed by grid current flow in the r-f amplifier, *V*2. The a-f plate current of the modulator tubes induces an a-f voltage in the secondary of the modulation transformer, *T*4. This induced a-f voltage is in series with the d-c plate voltage applied to the r-f modulated amplifier. Choke *L*5 and bypass capacitor *C*7 prevent the flow of r-f currents from the r-f modulated amplifier to the power supply. R-f transformer *T*1 consists of the r-f modulated amplifier tank coil and a coupling coil which goes to the antenna. Coupling between the coils is made variable to permit correct load matching between the r-f modulated amplifier and the antenna.

84. High-Power-Modulated Radiotelephone Transmitter

a. R-F Circuits.

(1) The r-f circuits in the transmitter shown in figure 134, are typical of those found in many military transmitters. The oscillator, *V*1, uses a modified electron-coupled circuit with *L*1 and *C*31 as its tuned circuit. R-f chokes *L*2, *L*3, and *L*4 prevent r-f currents in the grid and cathode circuits from entering the d-c power supply. Operating bias is provided by resistor *R*1. The transmitter is controlled by opening and closing key S in the cathode circuit of the oscillator. The r-f voltage on the oscillator plate is fed to the grid of buffer doubler *V*2 through capacitor *C*13.

(2) The current through *L*6 and *R*23 develops the *operating bias* voltage for this stage. Cathode resistor *R*24 develops sufficient *safety bias* to limit the buffer plate current to safe values with key *S* in the up position. *C*8 is the cathode bypass capacitor which prevents degeneration. Resistor *R*25 and capacitor *C*4 are the screen dropping resistor and bypass capacitor, respectively. Tank circuit *C*32 and *L*7 is tuned to the second harmonic of the oscillator. *C*26 is a plate bypass capacitor, *L*8 is an r-f choke, and *M*2 is the plate-current meter for the buffer doubler stage.

(3) *C*14 couples the output of *V*2 to the intermediate power amplifier consisting of two beam power tubes, *V*3 and *V*4, in parallel. The power amplifier stages can be operated as doublers or as straight amplifiers. The use of a beam power pentode eliminates the need for neutralization in these stages. *R*21 and *R*22 balance the grid excitation to the two tubes and minimize the possibility of parasitics. The output of this stage is fed to a power amplifier, *V*5, through *C*15. *C*18 is the neutralizing capacitor for the triode power amplifier. *T*4 and *C*12 comprise the tank circuit. The output of this stage is coupled from the secondary of *T*4 to the antenna. Bias for the intermediate amplifier and power amplifier stages is taken from the bias rectifier, *V*6. The power transformer is *T*1, *L*16 and *L*17 are the chokes, and *C*20 and *C*21 are the filter capacitors. The positive side of the supply (the rectifier filament) is grounded, and the voltage at the top of *R*11 is negative in

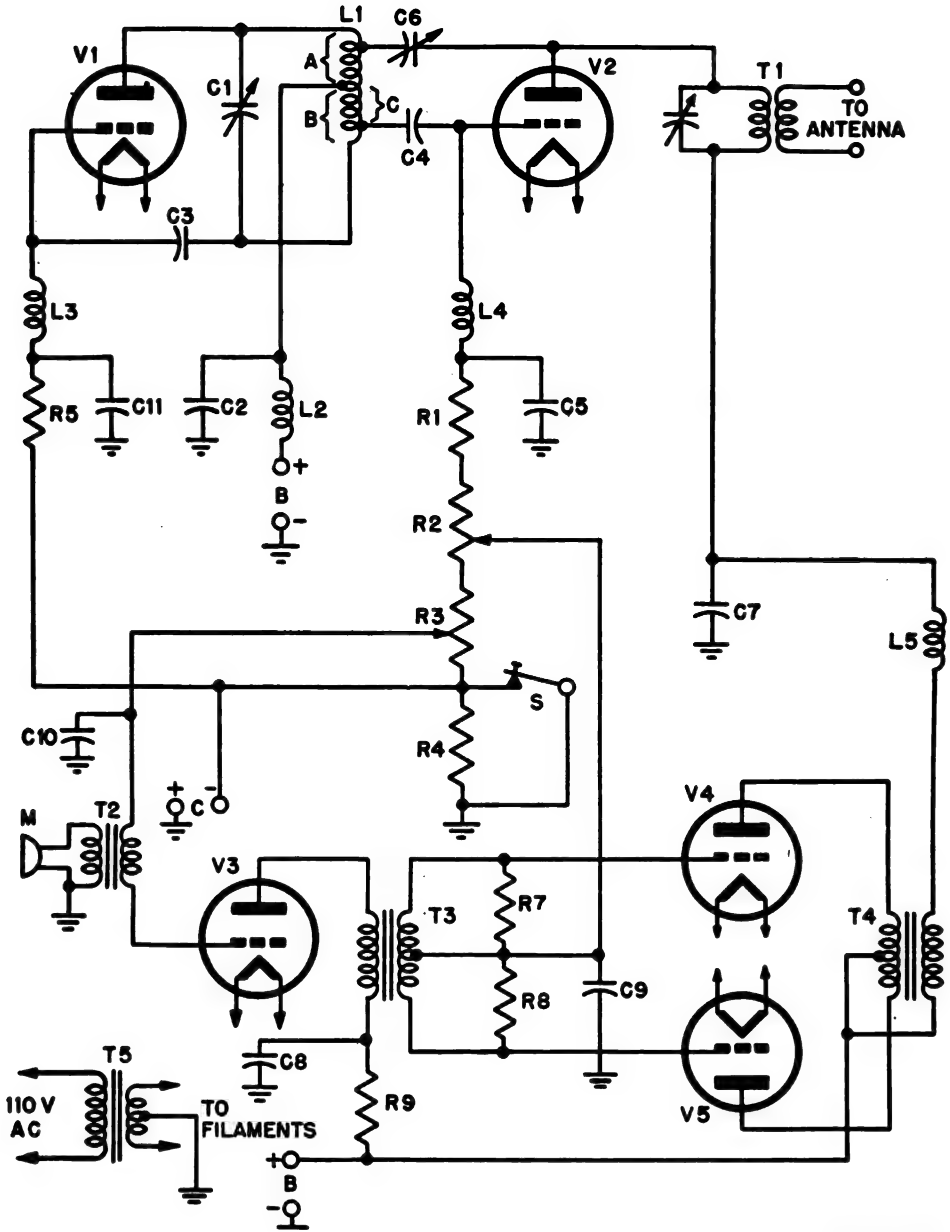

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Figure 133. Circuit of a low-power radiotelephone-telegraph transmitter.

respect to ground. The exciter rectifier supplies B plus to the oscillator. This circuit should be compared with that of the bias rectifier, *V*6.

b. A-F Circuits. The audio circuit is similar to the driver and modulator circuits described previously. The a-f speech amplifiers are coupled to the modulator driver, *V*11 and *V*12, through transformer *T*7. Fixed bias for the modulator driver stage (−60 volts) is developed across resistor *R*30 in the negative leg of the driver power supply. B plus for the modulator-driver stage (+300 volts) is developed across resistor *R*29. An example of a rectifier chassis for low-voltage and modulator voltage supply is shown in figure 135. *T*8 is the modulator driver transformer which couples the driver plates to the grids of the modulator stage, *V*13 and *V*14. Fixed bias for the modulator stage is obtained from potentiometer *R*12. *T*9 is the modulation transformer. Plate modulation is used for a high power output. Plate voltage for the modulator is applied

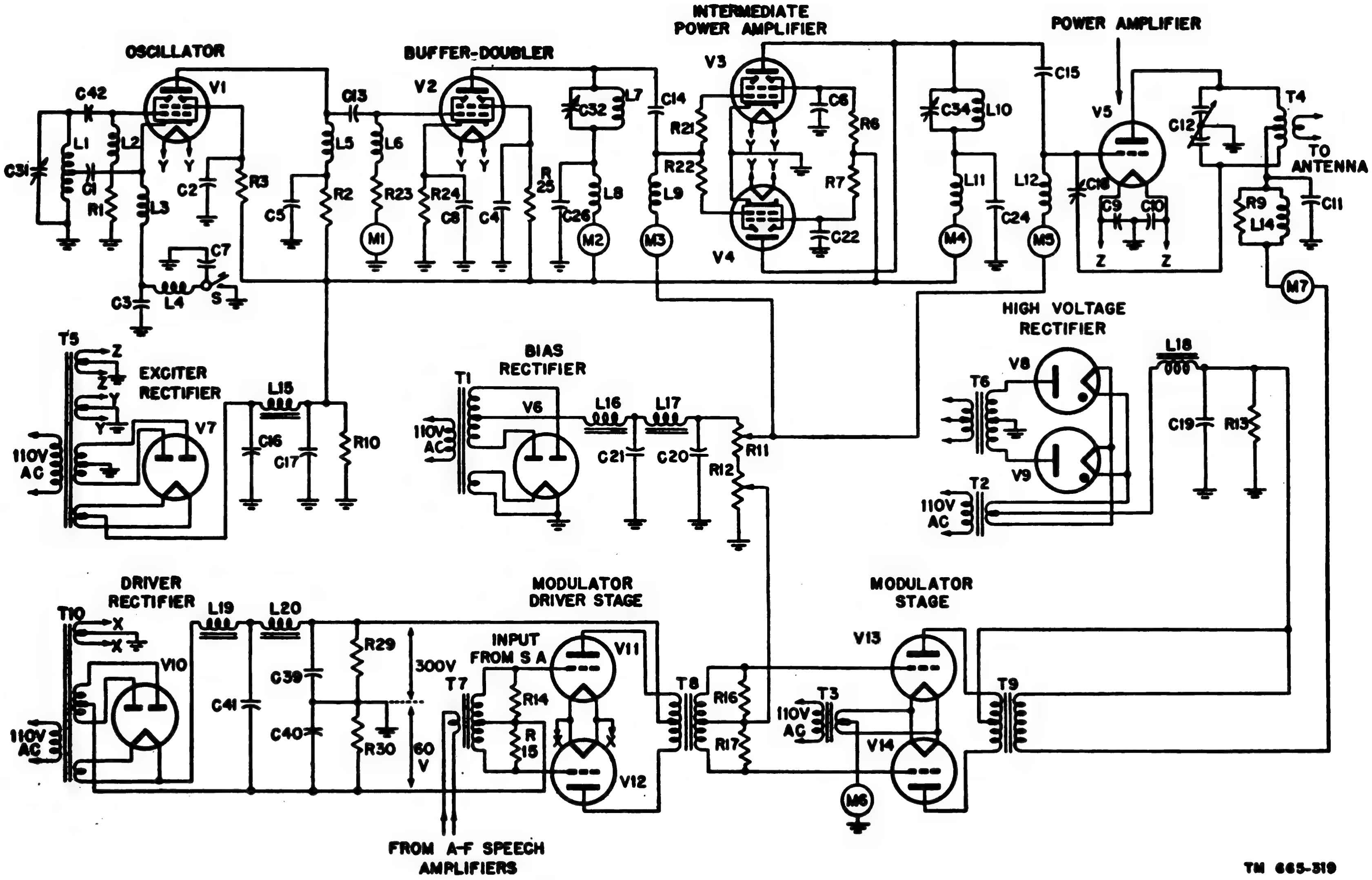

Figure 134. Circuit of a high-power radiotelephone transmitter.

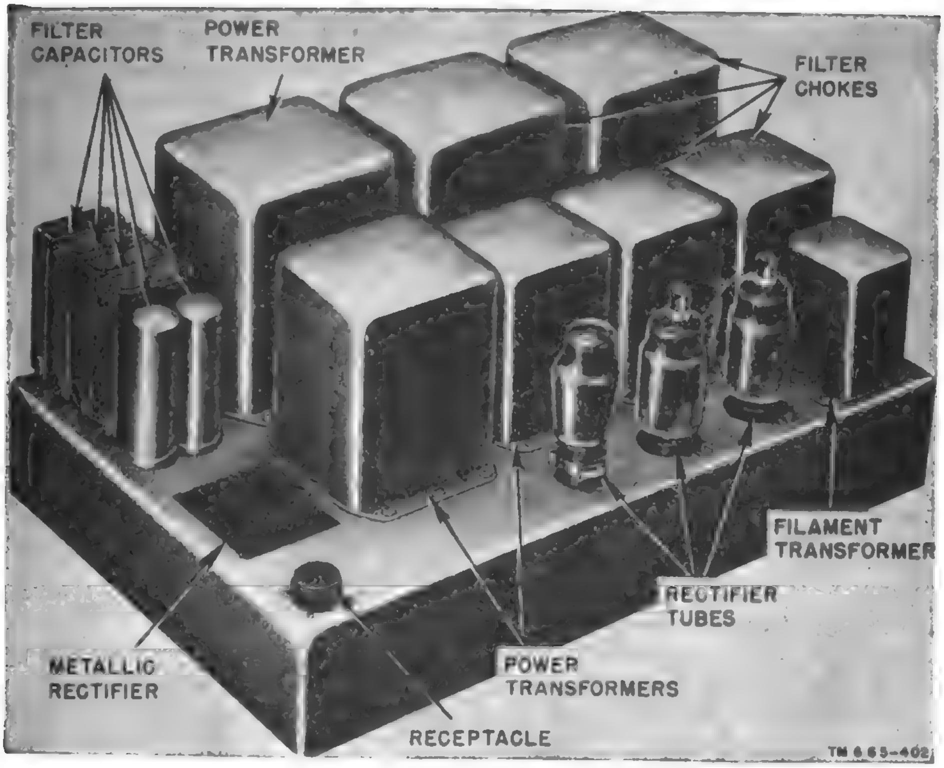

Figure 135. Transmitting type rectifier chassis for low-voltage and modulator-voltage supply.

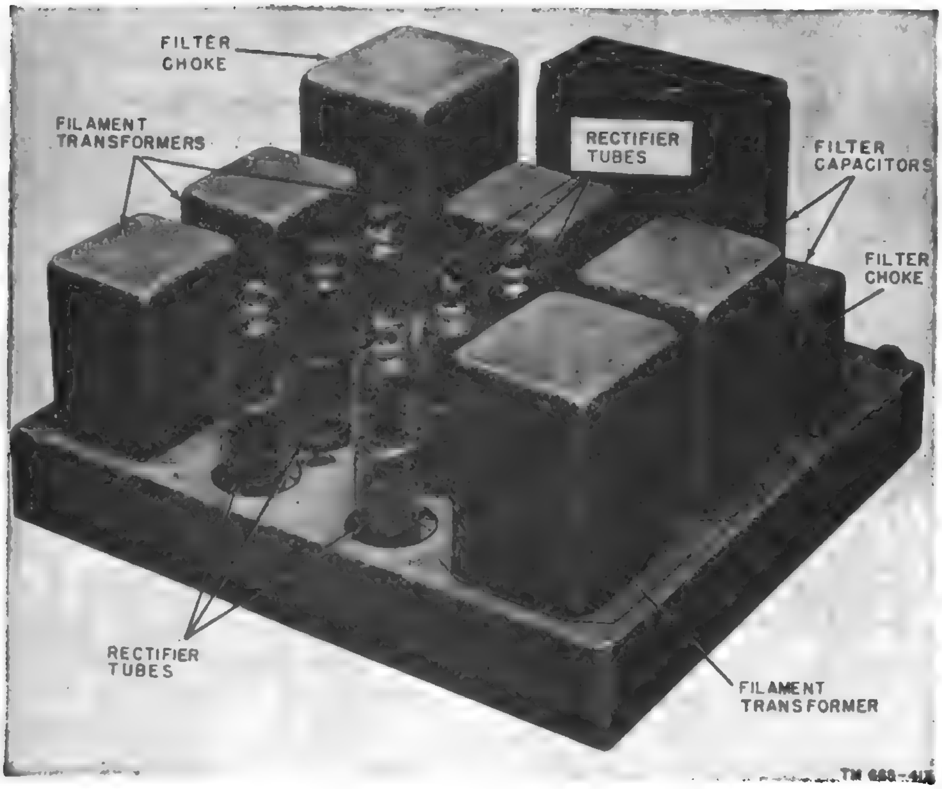

Figure 136. High-voltage chassis for transmitter.

to the primary of *T*9 and voltage for the power amplifier is applied to the secondary of *T*9 from *V*8. A typical high-voltage chassis for a transmitter is shown in figure 136. Meters M6 and M7 measure the modulator and power amplifier plate currents, respectively.

85. Modulation Indicators

a. General. If a transmitter is not fully modulated, the power in the side bands is low and the effective transmitting range is reduced. On the other hand, if the transmitter is overmodulated, the signal is distorted and may be broad enough to blanket stations operating on channels far from the offending transmitter.

b. Oscilloscope for Checking Modulation.

(1) A number of instruments have been designed or adapted for checking the modulation percentage of amplitude-modulated transmitters. The oscilloscope is the most useful of these. It is the most accurate and provides a picture of the modulation percentage. Two types of patterns can be observed on the oscilloscope. One is known as the *wave envelope* and the other the *trapezoid.* This manual is concerned only with the wave envelope type.

(2) Connections for wave envelope measurement (fig. 137) are the easiest to make. A testing coil consisting of a few turns of wire is connected to the vertical de-

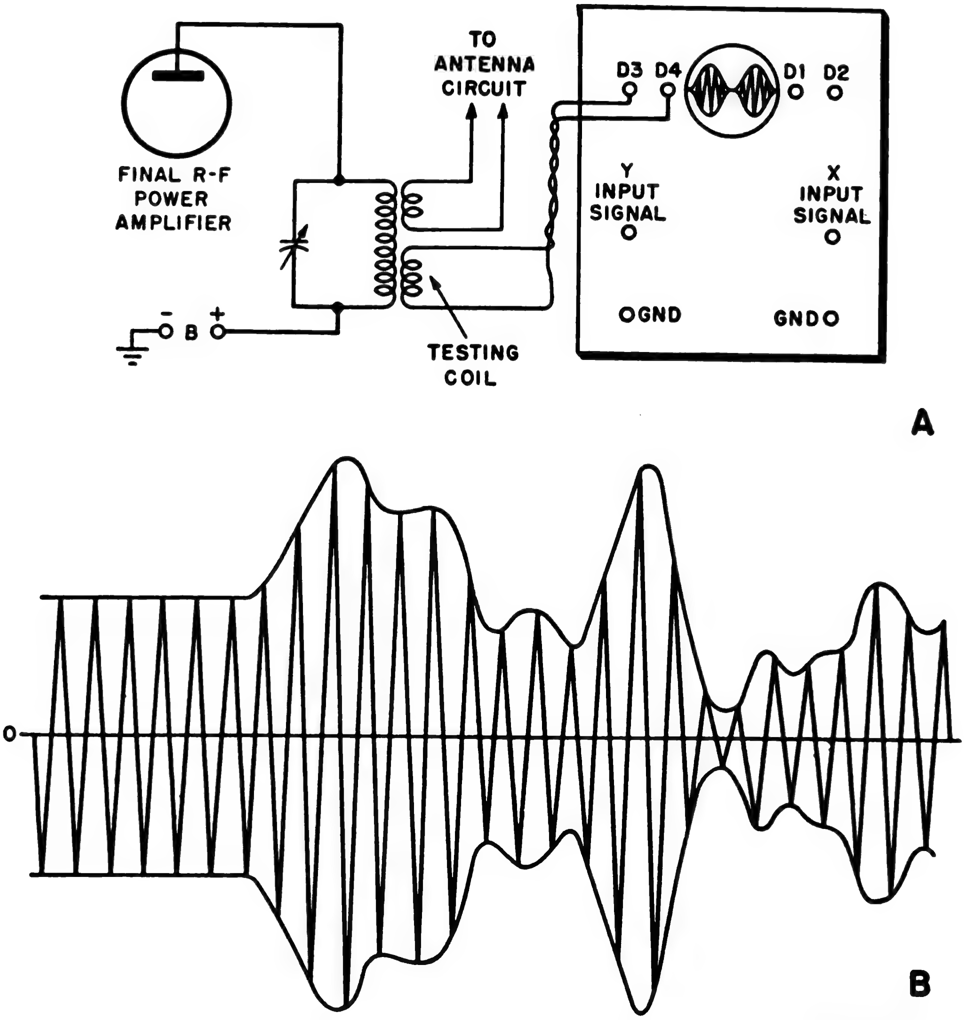

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Figure 137. Oscilloscope measurement of modulation percentage and waveshape.

flection plates of the oscilloscope, *D3*, and *D4*, through a length of twisted wire. When this coil is placed near the tank coil of the final r-f power amplifier, the sweep produces a modulation envelope of the transmitter output. The sweep generator in the oscilloscope is adjusted to a frequency lower than the lowest modulation frequency. The modulation factor or percentage of modulation can be found by making the necessary calculations, using the modulation formula that was discussed previously. A complex speech wave is similar to that shown in B, figure 137. It is more difficult to calculate the percentage of modulation from such a wave envelope because of its complexity. However, wave envelope measurements for voice or music can be checked easily for 100-percent modulation by watching the zero line of the pattern. Percentage of modulation calculations should be made only when a simple modulation pattern appears on the face of the scope. A bright spot will appear in the trough at the instant that the transmitter is overmodulated.

86. Cooling High-Power Transmitting Tubes

a. The temperature of a large transmitting tube must be kept as low as possible for several reasons. If the plate gets too hot, it may radiate enough heat to cause the grid to emit electrons. The intense heat may release residual gases from the plate and other tube elements. The glass envelope or tube elements may get hot enough to warp or even melt. Tubes capable of operating with inputs up to approximately 1,000 watts usually have glass envelopes. The heat from the plate must be radiated through the envelope. Since the tube operates more efficiently when running comparatively cool, transmitter components usually are laid out so that there is an unobstructed flow of air around the tube envelope. When the plate dissipation rating of the tube is above approximately 350 watts, forced-air cooling must be used. Small fans or blowers are used to force a steady stream of cool air over the tube.

b. When the plate dissipation of the tube runs to several kilowatts, the plate of the tube usually is constructed as a copper cylinder which forms a part of the envelope. Tubes for forced-air cooling usually have metal radiating fins attached to the plate to provide a greater heat radiating surface. Air-cooled tubes which have an external plate usually have a very large output capacitance which makes them unsuitable for use at very high frequencies.

c. Water cooling is used also for tubes having a high plate dissipation rating. Such tubes are constructed with a water jacket surrounding the plate. A thin, high-velocity stream of water keeps the plate reasonably cool. Special precautions must be taken to prevent short circuiting the plate to ground. One method of doing this is to arrange for the water to and from the plate to pass through coils consisting of several hundred feet of ceramic or plastic tubing. Since there is no metallic connection between plate and cooling system, the water provides the only leakage path between plate and ground. By using distilled water, the resistance is kept sufficiently high to limit the leakage current to a very small percentage of the plate current. Most water-cooled systems are fitted with special controls which turn off the transmitter when the leakage current exceeds a given value or when the pumping system fails.

87. Filament Construction, Plate Voltage, and Current Ratings

a. The coated cathode is highly efficient and radiates more electrons for a given power input than does a directly heated filament. It does not radiate heat as rapidly as does an ordinary filament. Coated cathodes are used most often in tubes which operate with maximum plate voltages below 1,000 volts, and in special pulse type tubes in which large values of plate current flow for short periods of time. Cathodes are not particularly suited for use in tubes which carry heavy plate currents for long periods of time because the coating has a tendency to flake off when high current is drawn.

b. Thoriated-tungsten filaments generally are used in transmitting tubes operating with plate voltages not exceeding 5,000. The thin thorium coating tends to deteriorate when operating in a tube having a high residual gas content. Such tubes should be operated at precisely the rated voltage for maximum life. Pure tungsten filaments are used in large power amplifiers, particularly those operating with very high plate voltages. The life of a tube having a pure tungsten filament is doubled by a 5-percent decrease from the rated filament voltage; a 5-percent increase reduces the life by about one-half. A 10-percent decrease in normal filament voltage quadruples the tube life; a 10-percent increase reduces it to one-quarter of its normal life. The life of a tube usually is determined by the life of its cathode or filament. Small power tubes last about 2,000 hours; larger ones may last 10,000 hours or more. Some very large tubes have filaments that can be removed for replacement. The vacuum is maintained by pumps while the tube is in operation.

c. In any vacuum tube, the peak plate current that can be drawn is determined by the power input and efficiency of the filament. The filament voltages for most small tubes are those voltages which can be supplied from a standard source such as a 6-volt storage battery. The current rating of the filament is adjusted to supply the necessary filament power. For example, tube type JAN–807 has a 6.3-volt, .9-ampere heater which can be supplied from a standard 6-volt vehicular storage battery. A 1625 type tube is the electrical equivalent of an 807 with the exception of heater voltage and current. This tube has a 12.6-volt, .45-ampere heater which makes it especially useful for service in aircraft and vehicles having 12-volt primary batteries. In each case, the power input to the heater is 5.67 watts.

d. For a given maximum plate power input, there are a number of tubes which have the same plate dissipation and vastly different maximum plate voltages and currents. Some tubes, particularly those having tantalum plates, operate with comparatively high plate voltage and low plate current; a similar tube having a carbon plate is likely to have twice the maximum plate-current rating and one-half the current rating.

88. Safety Precautions

a. Most transmitters operate with plate voltages of 250 volts or higher. Contact with these voltages can cause a serious shock or even death. It is, therefore, necessary to be especially careful when making transmitter adjustments. This is particularly true when changing coils, crystals, tuning units, or when neutralizing the transmitter.

b. When the power is turned off in most transmitters, the bleeder and voltage divider resistors discharge the filter capacitors. Occasionally, one or more of these resistors open and prevent the filter capacitors from discharging properly. If body contact is made to a charged capacitor, the capacitor can discharge through the body and can cause shock, severe burns, or even death.

c. Most transmitter with an output of a hundred watts or more are equipped with switches, relays, or timing devices which open the primary circuits to certain high-voltage circuits whenever the doors to a transmitter are opened. Sometimes a switch, for example, may be defective so that a high-voltage circuit may continue to receive power even with a transmitter door open. At such times, the transmitter is even more dangerous than a charged capacitor for the maintenance man who may come in contact with it. As a precaution against accidental shocks, make sure that no high voltages are present and discharge all capacitors before performing preventive maintainance or troubleshooting on a transmitter. The most convenient and the safest method of discharging capacitors is with a shorting stick (fig. 138).

d. To construct a shorting stick, fasten a piece of copper, brass wire, or brass tubing to the end of a dry piece of wood, bakelite, or other insulating material, about 3 feet long and a few inches square. The wire or rod should extend approximately 1 foot beyond the end of the stick and this extension is bent to form a hook. Solder a 2-foot piece of heavy flexible wire or braid to the metal at the point where it is fastened to the stick, with a heavy battery clip attached to the free end of the wire.

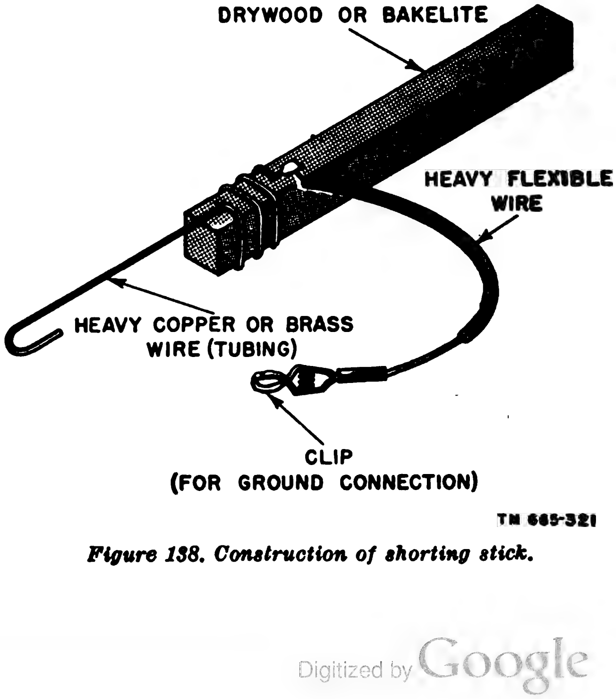


Figure 138. Construction of shorting stick.

e. In use, connect this clip to the transmitter chassis (ground connection) near the capacitor to be discharged, or to the part that is to be touched. Holding the shorting stick by its wooden handle, touch the metal hook to the capacitor or component part to be worked on.

f. When working on a transmitter, *always keep one hand in pocket;* also avoid working on electrical equipment while standing on a concrete or damp floor. When trouble shooting in pairs, never take the word of a coworker for anything that might affect personal safety, and never rely on him to turn off the transmitter. This is particularly important when the equipment must be turned on and off many times during an adjustment or trouble-shooting procedure.

89. Summary

a. Amplitude modulation is a process by which the amplitude of an r-f carrier wave is made to vary in accordance with the waveshape of the modulating a-f voltage.

b. When the modulating a-f voltage consists of more than a single frequency, separate side frequencies are generated by each modulating frequency.

c. A group of side frequencies is called a side band.

d. The upper side band contains frequencies equal to the r-f carrier frequency plus each individual modulating frequency. The lower side band is equal to the r-f carrier frequency minus each individual modulating frequency.

e. A modulated signal occupies a channel or band of frequencies equal to twice the highest modulating frequency.

f. The intelligence of an amplitude-modulated signal exists solely in the side bands, the amplitudes of which vary according to the strength of the modulating signal.

g. The carrier amplitude is constant with and without modulation.

h. The envelope of a modulated wave must correspond exactly to the shape of the modulating signal for distortion-free modulation.

i. The power in the side bands is determined by the percentage of modulation.

j. For 100-percent modulation, the total side-band power is one-half the carrier power.

k. Modulation in excess of 100 percent causes interference to stations on adjacent channels and causes distortion in the received signal.

l. The percentage of modulation depends on the amplitude variations in the envelope and not on the amplitude of the unmodulated carrier.

m. A high percentage of modulation (near 100 percent) produces a high signal-to-noise ratio in the received signal. It provides greater area coverage for a given carrier power and provides for less interference from stations operating on adjacent channels.

n. The r-f circuits of an amplitude-modulated transmitter are often exactly like those of a c-w transmitter of the same frequency and power output.

o. Many transmitters are designed for either c-w or radiotelephone operation.

p. The modulator is the a-f stage which supplies the necessary modulating voltage or power to the r-f circuit being modulated.

q. In some low-power transmitters, the modulator grid or grids may be driven directly by a carbon microphone.

r. In others, considerable voltage and/or power may be required between the microphone and the modulator grids.

s. The circuit or circuits which provide the necessary a-f amplification make up the speech amplifier.

t. When power is required on the modulator grids, it is supplied by a class A or class AB power amplifier called a modulator driver for minimum distortion.

u. The microphone most often used in military transmitters is the carbon microphone.

v. The carbon microphone consists of one or two buttons containing carbon granules which are compressed and released by a diaphragm which vibrates when sound waves strike it.

w. The resistance between the carbon granules varies with pressure. Therefore, when a voltage is applied to the microphone, the current through it varies in accordance with the sound waves striking the diaphragm.

x. The changes in current are converted into an a-c voltage through the action of the transformer which couples the low impedence microphone to the high impedance grid circuit of the first speech amplifier.

y. Dynamic and velocity microphones operate on the basis of a voltage being induced in a conductor which moves within a magnetic field in accordance with sound waves striking it.

z. A condenser microphone is similar to a small variable capacitor, the changing capacitance of which produces a varying voltage in the grid circuit of an a-f voltage amplifier.

aa. Modulation systems are classified either as variable efficiency, constant input or constant efficiency, variable input.

ab. In plate-circuit (Heising) modulation, the modulator supplies an a-f voltage which is in series with the d-c plate voltage to the plate of the modulated r-f amplifier.

ac. This voltage adds to the r-f plate voltage on one half cycle and subtracts from it on the next.

ad. For 100-percent modulation, the peak a-f voltage must equal the d-c plate voltage on the modulated r-f amplifier.

ae. Since the instantaneous power input is higher for a plate-modulated amplifier than for c-w operation, the d-c input should be reduced to approximately two-thirds the maximum value for c-w.

af. Grid bias, screen grid, and suppressor modulation are all constant input, variable efficiency modulation systems.

ag. The a-f power required for these methods is considerably lower than that required for plate modulation.

ah. Since the plate efficiency of the modulated r-f amplifier is lower for grid modulation than it is for plate modulation, the permissible power input and power output for grid modulation are correspondingly lower than for plate modulation.

ai. When the modulator is operated class A, its peak grid signal voltage should be equal to the d-c bias for maximum power output.

aj. Class AB1 modulators are biased slightly higher than class A modulators and the peak grid voltage is equal to or slightly less than the d-c bias.

ak. Class AB2 modulators are biased and driven so that the plate current flows for more than one-half but considerably less than the full excitation cycle.

al. Class B modulators are operated with substantially zero plate current with no a-f signal input.

am. The ideal tubes for class B service are high-mu triodes and those designed so that the plate current is nearly zero without grid bias. Such tubes are called zero bias tubes.

an. The characteristics of speech are such that the average percentage of modulation is low, approximately 30 percent, when the transmitter is adjusted so that the tips of occasional peaks represent 100-percent modulation.

ao. A system used to provide for a higher percentage of modulation without overmodulation is called *volume compression* (or automatic modulation control). In this system a portion of the speech voltage is rectified to produce a negative biasing voltage which is applied to the suppressor grid of one of the a-f speech amplifier tubes.

ap. The rectifier is biased so that the negative biasing voltage is not developed until the average modulation percentage is 80 percent or higher.

aq. Above this predetermined level of modulation, the rectifier produces a negative bias which reduces the gain of the a-f speech amplifier.

ar. Another method of preventing overmodulation is to use speech clippers.

as. A low level clipper consists of two rectifiers (back-to-back) across the output of an a-f speech amplifier stage.

at. These rectifiers are biased so that they conduct and short circuit any a-f signal above the level which produces 100-percent modulation.

au. A high level speech clipper consists of a high-voltage rectifier in series with the B-plus supply lead to the modulated r-f amplifier.

av. The rectifier conducts and delivers plate voltage to the modulated r-f amplifier as long as the instantaneous voltage on its plate is positive in respect to ground.

aw. To keep the temperature of a large transmitting tube comparatively low, small fans or blowers are used to force a steady stream of cool air over the tube.

ax. Water cooling is used also to keep the temperature down in transmitting tubes. The tubes are constructed with a water jacket surrounding the plate.

ay. When working on a transmitter, always keep one hand in pocket, and never work on electrical equipment while standing on a concrete or damp floor.

az. Always use a *shorting stick* to discharge capacitors before working on them.

90. Review Questions

a. Name the different types of modulation.

b. What is amplitude modulation?

c. Define a side band.

d. How does amplitude modulation affect the amplitudes of the carrier and side bands?

e. How can you determine the percentage of modulation of a modulated waveform?

f. What effect does the percentage of modulation have on the over-all performance of an amplitude-modulated transmitter?

g. What are the effects of overmodulation on the radiated signal?

h. What is the ratio between carrier and side-band power for 100-percent modulation?

i. Is there a major difference between the r-f circuits in c-w and high level amplitude-modulated transmitters of the same carrier power?

j. What is the purpose of the modulator?

k. Define high and low level modulation and name at least one method of obtaining each type.

l. How can you identify the method of modulation commonly referred to as Heising modulation?

m. Why is Heising modulation sometimes called constant current modulation?

n. Why is a class A amplifier impractical as a high level plate modulator?

o. Why is transformer coupling generally used between the modulator and the plate-modulated r-f amplifier?

p. What special precaution must be observed when plate modulating a screen grid tube?

q. How can minimum distortion and maximum efficiency in a plate-modulated class C amplifier be obtained?

r. Explain why grid-bias modulation is a variable efficiency constant input system.

s. Explain why the efficiency of a cathode-modulated amplifier may vary over a wide range.

t. Name four basic types of microphones.

u. Give one reason why a carbon microphone is commonly used in military radiotelephone transmitters.

v. What are the power requirements of an a-f speech amplifier?

w. Name two advantages of resistance capacitance coupling.

x. Name one advantage and one disadvantage of transformer coupling.

y. Draw the circuit and explain the operation of one type of phase inverter.

z. What are the power requirements of a driver for a class B modulator?

aa. Can modulators be operated without bias?

ab. Why must the plate and bias voltage supplies for a class B modulator have good regulation?

ac. Is it always possible to determine the class of operation of a modulator merely by studying the circuit arrangement?

ad. Describe the process of automatic modulation control or volume compression.

ae. Give the immediate effect on a transmitter signal when the filter is removed or short circuited in a speech clipper circuit.

af. Explain how you would use an oscilloscope to measure percentage of modulation of an a-m transmitter with speech input.

CHAPTER 6

AUXILIARY CIRCUITS

91. General

a. Functions.

(1) In order to function properly, a transmitter must contain not only the basic stages, such as the oscillator, modulated r-f amplifier, and modulator, but also a number of additional circuits, known as *auxiliary* or *control* circuits. These circuits perform three general functions. They control the start-stop operations of the transmitter, protect equipment, and protect personnel.

(2) A control circuit may perform such functions as turning on filament voltage, or plate and screen voltage. This is done indirectly through an auxiliary circuit rather than directly by the operator. Auxilary control circuits are used, for example, when the circuit to be adjusted is beyond the reach of the operator, when it is necessary to turn on a large number of circuits simultaneously, or when it is required to have an accurate time delay between one operation and the next. In addition, self-acting auxiliary circuits are used because they reduce the chances of human error. For example, they prevent the operator from turning on the high voltage before the filament voltage which prevents possible damage to tubes.

(3) In the course of transmitter operations, conditions harmful to the equipment may appear. These include excessive current, excessive voltage, excessive temperature rise, and others. Best protection against equipment damage is provided by automatic devices operating through auxiliary circuits. Commonly, these do not remedy the trouble but merely interrupt operation, consequently preventing damage to the equipment. Whenever dangerously high voltages are used in equipment, serious or fatal accidents may occur. The percentage of such accidents can be reduced by providing automatic protection for personnel through auxiliary circuits. One common protective circuit is known as a *door interlock*. This de-energizes high-voltage equipment whenever the door or panel that gives access to such equipment is opened. The protection provided is not absolute (filter capacitors may still remain charged) but it reduces the risk of personnel from coming in contact with the high voltage.

b. Signal Lamps. Auxiliary circuits are commonly equipped with signal lamps which are used as signaling devices. For example, if a protective auxiliary circuit interrupts transmitter operation, a lamp or lamps (usually colored) associated with this circuit go on. As another example, if warming up a transmitter for operation is accomplished through a number of steps automatically controlled by auxiliary circuits, the completion of each step of this process is indicated by suitable colored lamps. Signal lamps vary in size and type from very large, brilliant ones to tiny pilot lights. They are grouped together on the main control panel or are otherwise located wherever they are most likely to catch the eye of the operator.

c. Power Supplies.

(1) Most auxiliary circuits are associated directly or indirectly with the power supplies of communication equipment. These power supplies take many forms, depending on the source or primary power that are available and on the requirements of the equipment involved. Since receiver power supplies are discussed

later in this manual, only the power supplies for transmitters are examined here.

(2) In general, transmitter power supplies are much the same as receiver power supplies except that higher powers usually are required for the transmitter. Consequently, primary power sources must have greater capacities in order to deliver the higher powers needed. Where available, commercial power lines are used. Frequently, special lines are installed to accommodate the higher currents that are employed. Storage batteries sometimes are used to operate dynamotors or motor-generator sets. This rotating equipment either supplies the required voltages and currents directly or their outputs are connected to large rectifier units. These units rectify and filter the applied power so that it is in the proper form to be used for the transmitter. Gasoline driven generators frequently are used in field installations or as emergency sources of supply. The output of these units is frequently similar to that obtainable from the commercial power line.

(3) Polyphase voltage sources frequently are used for large fixed transmitters. Such sources are either commercial power lines or gasoline-driven generators. Polyphase restifiers are used to convert the alternating current obtained from the source into a form that will be useful for the transmitter involved. For a complete discussion of polyphase rectifier circuits, refer to TM 11–663.

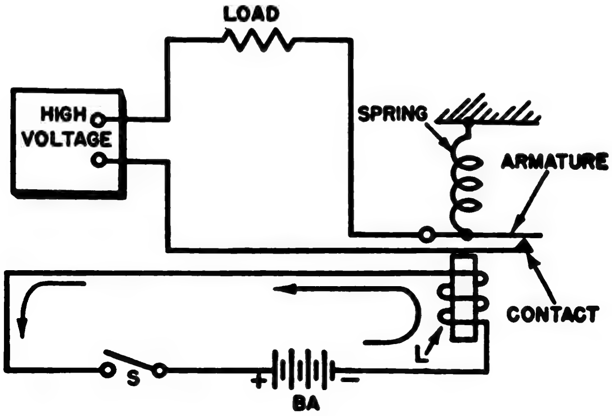
(4) Frequently it is necessary to employ some type of voltage regulation of both the power source and the output voltages. Such regulation is particularly important when transmitters must have a high degree of frequency stability. Various types of regulators are discussed in TM 11–663.

92. Relay Principles

a. The basic component in virtually all auxiliary circuits is the relay. A relay is a switch which is operated by electromagnetic action. It is constructed so that it will open or close one or more circuits when current through it is started, varied in strength, or stopped. The basic parts of a relay are a coil consisting of a large number of turns of wire wound around an iron core, an armature which operates the switch contacts, and a spring to return the armature to its normal position when the relay coil circuit is broken or the current through it is below the value required to attract and hold the armature.

Caution: Do not depend on safety switches (see par. 88).

b. A simple relay circuit and its practical use are shown in figure 139. When switch *S* is closed, battery current from *BA* flows through coil *L*, energizing it, and causing it to exert electromagnetic attraction to the armature. The attraction overcomes the tension of the spring and closes the contacts which complete the high-voltage circuit. The contacts remain closed until the operating switch is opened, de-energizing coil *L*. Whenever this happens, the spring tension draws the armature back to its original position.



TM 665-322

Figure 139. Simple relay circuit.

c. The time required to operate a relay varies widely with the type of relay used. A representative value is about .002 second. A representative value for the time required for the relay to release is about .005 second. In some applications, it is desirable to increase either the operating or releasing time. In this case, special type relays, known as *slow operating* or *slow releasing* relays, are used.

d. The relay shown in figure 139 can be made slow operating by inserting a metallic slug or shorted turn of wire at the armature end of the coil. The current induced in the shorted turn or slug retards the build-up of the magnetic field and, hence, the operating time. If the shorted turn is placed at the other end of the electromagnetic coil, the relay becomes a slow release type.

93. Control Circuit Relays

a. Introduction. Many types of relays are needed to meet the various requirements in transmitter circuits. As some examples, a relay must be capable of passing a high current or high voltage, it must operate several switches simultaneously, or it must close several switches in a given sequence. A common type of relay found in transmitters is the *switchboard type* shown in figure 140. Other comon types are the clapper and the solenoid type.

b. Switchboard type. The switchboard type relay (fig. 140) is available with either a single set of contacts or with several sets of contacts all operated by the same coil. Normally, some of the contacts may be opened and closed when the coil is energized; others may be opened and closed when the coil is de-energized. The copper collar, or sleeve, is used on the relay to provide delay action.

c. Clapper type. Relays of the clapper type construction (fig. 141) are favored for use in controlling heavy currents, and therefore, are often referred to as *contactors.* The relay has a swinging armature which is pivoted at one end. The contacts are mounted at the free end. When the relay is energized, the armature contacts are snapped against the stationary ones with a clapping action. This clapper action causes the contacts to come together with a sliding motion which tends to make them self-cleaning, thereby insuring a good contact.

d. Solenoid Type. In most relays the magnetic coil is wound on a solid core. The solenoid or power contactor type differs from the others in that the coil is open core and the moving element is drawn vertically not only to the end of the coil but also, in some cases, into the hollow stem. Consequently, the moving element can be given a longer stroke and can move over a greater distance. The solenoid relay shown in figure 142 is a-c energized. Its armature snaps upward, closing contacts which are mounted on springs to assure uniform pressure. Since the armature is mounted vertically, gravity alone returns it to the resting position when the coil is deenergized.

e. Polar Type. A polar relay is shown in figure 143. The coil that is wound around the armature polarizes it so that the armature is attracted to either pole piece, *P*1 or *P*2, of the horseshoe magnet. With no current flowing through the coil, the armature remains in the position shown. If the current through the coil is such that the top of the armature becomes N (north), then the armature is attracted to pole piece *P*2 which is polarized S (south). Contact *C*2 closes.

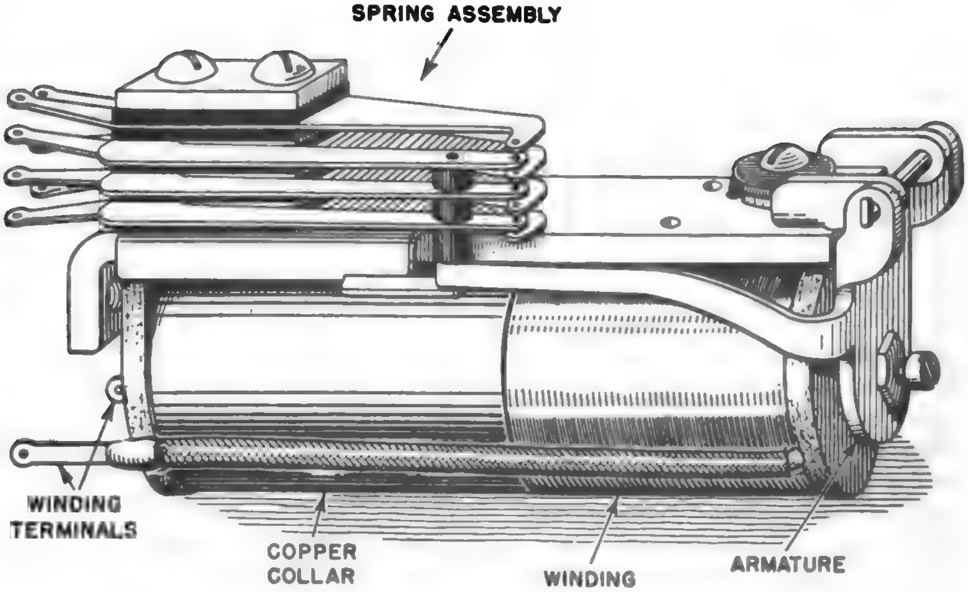
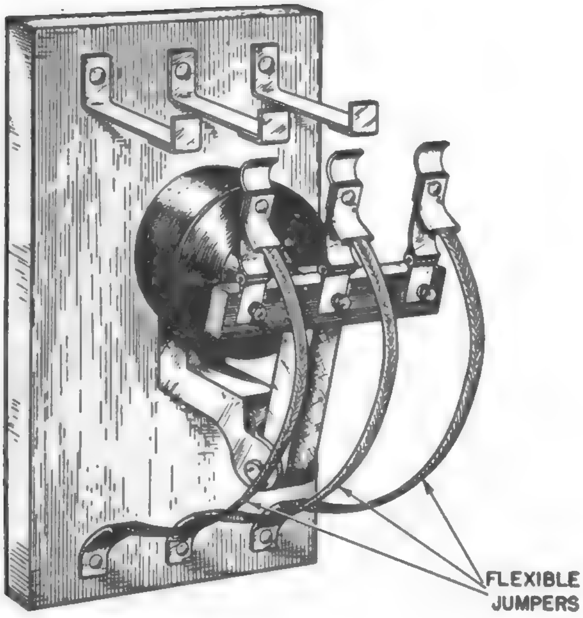
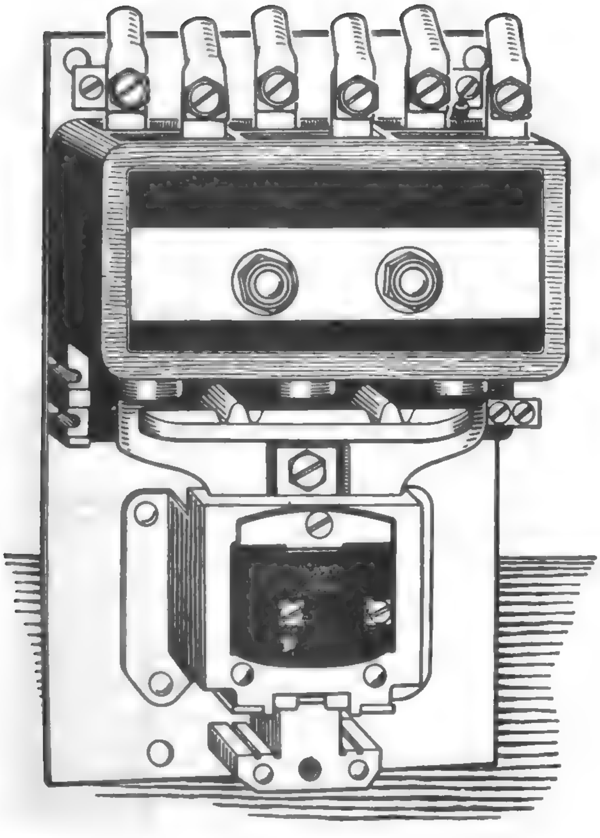


Figure 140. Switchboard type relay.



TM 665-324

Figure 141. Clapper-type contactor.



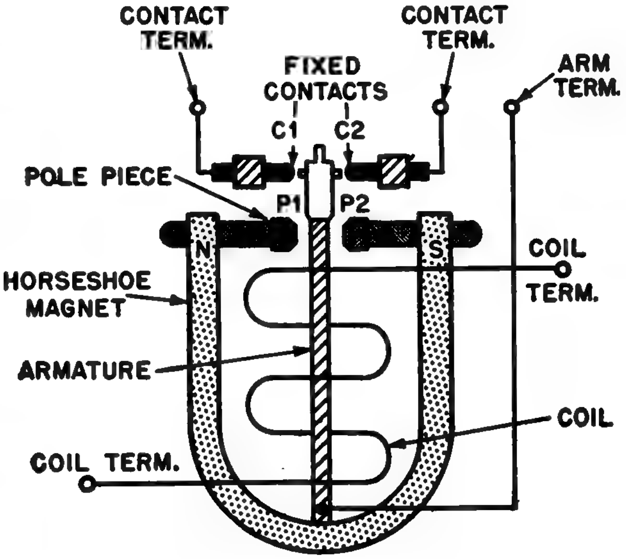
TM 665-325

Figure 142. Solenoid-type power contactor.

Conversely, if the current through the coil is reversed, then the armature is attracted to $P1$. Contact $C2$ opens and $C1$ closes. Consequently, this relay is used to close or open a circuit depending upon the direction of current flow through the coil.

94. Circuit Protection

A number of types of relays are used to protect circuit components from damage. Relays which protect a circuit from the flow of excessive current are called *overload* relays. In some circuits, on the other hand, it is important to prevent the application of voltage unless a certain minimum amount of current is flowing. For this purpose, an *underload* relay is used. In most high-power stages, the filaments must heat up before high voltage can be applied to the plate of the tube. It is, therefore, necessary to delay the application of high voltage, and therefore, a *time delay* relay is used. In addition to relays, there are other components, such as fuses and circuit breakers, which can be used to protect circuits. Some of the common circuit protective devices are discussed below.



TM 665-326

Figure 143. Polar relay.

95. Overload Protection

a. Overload Relay with Electrical Release. The contacts of the overload relay (fig. 144) will open when the current through the overload coil exceeds a certain predetermined value. As long

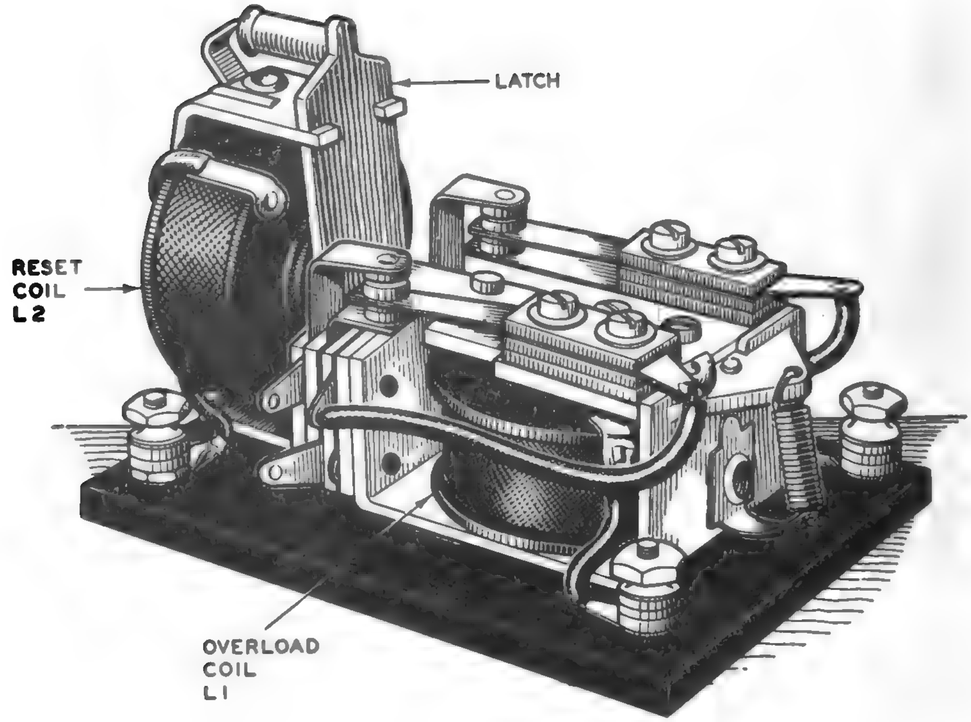


Figure 144. Overload relay with electrical reset.

as the current flow is below this value, the armature is not actuated by the overload coil. However, when the current through this coil exceeds the maximum permissible value, the armature pulls in and opens the contacts. These contacts then are held open by a mechanical latch until released by the operator. Reset coil $L2$ is an electrical release for this purpose. In other types the release is effected mechanically.

b. Overload Relay (Adjustable Type). Figure 145 shows an overload relay that protects an amplifier stage. A variable resistor, R, is in parallel with the overload coil. Any surge of excessive current that flows through the amplifier divides between the overload coil and resistor R. The percentage that flows through the overload coil depends on the setting of the resistor. If the resistor arm is moved to the right, most of the current flows through the resistor and only a comparatively large current flow can actuate the armature. As the contact is set farther to the left, more and more current flows through the coil and a comparatively weak current surge can pull the armature and break the circuit. When the relay is actuated, the power input line to the high-voltage power supply is opened and the amplifier stage does not obtain B plus. A mechanical latch is used to reset the relay. Figure 146 shows a typical overload relay used in a military transmitter.

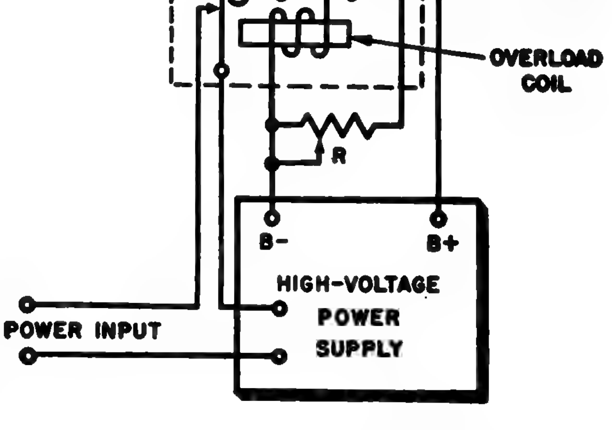


Figure 145. Circuit using an overload relay.

Figure 146. Typical overload relay.

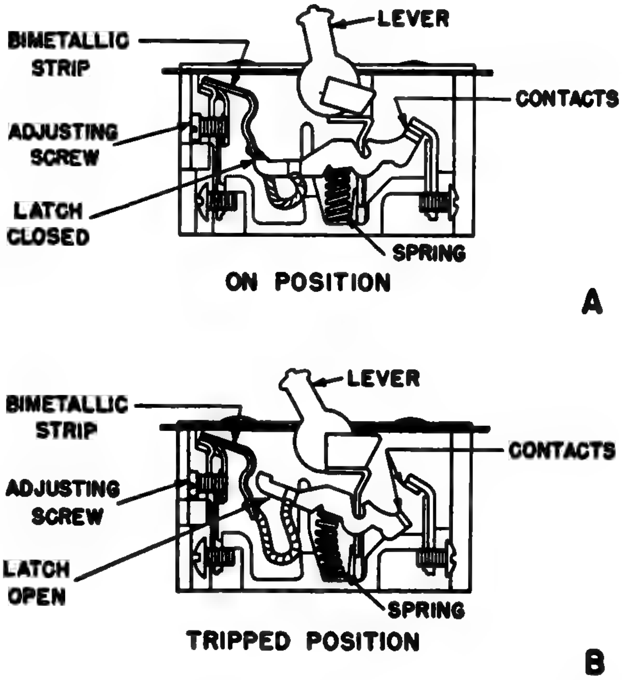
c. Thermal-Action Circuit Breaker.

(1) A circuit breaker is a switch that opens a circuit when a current in excess of a certain value flows through it. The overload relays previously described are circuit breakers that depend on magnetic action. Other circuit breakers depend on thermal action. The thermal circuit breaker is operated either by a separate heater element and a bimetallic strip or by passing current through the strip itself to generate heat (fig. 147).

(2) In A, the circuit breaker is shown in the normal position, the semiflexible bimetallic strip holding the latch down as the spring tries to force it up. In this position the contacts are closed. The heat generated in the bimetallic strip varies with the magnitude of the current flowing through it. Heat causes it to bend, and when the current reaches an excessive value, the strip bends sufficiently to release the latch and open the contacts. The lever is used to reset the circuit breaker. A unit of this type carries its rated load indefinitely. It can carry a 50-percent overload for approximately 60 seconds, a 100-percent overload for about 10 seconds. A 200-percent overload causes the circuit breaker to trip in about 5 seconds. This type of circuit breaker often is used to protect dynamotors and similar devices having large starting currents which do not last for more than a few seconds.

(3) Thermal circuit breakers of this type do not act as fast as magnetic units. Time is needed for the temperature to rise and produce the desired action, whereas magnetic types can be set to operate almost instantaneously. The thermal relay, therefore, can be used where some degree of temporary overload is to be expected from time to time and can be tolerated if it does not last too long. The magnetic type is preferred where either quicker or more accurate response is needed.

d. Common Fuse Types. The most common over current protective device is the fuse. A fuse consists of a short length of metallic ribbon or wire (fuse link) that is inclosed in a fuseholder. Its composition consists of a metallic alloy having a comparatively low melting point. The amount of



TM 665-329

Figure 147. Thermal type circuit breaker.

current the fuse can carry without melting depends on its cross section and on the type of alloy used. Melting of the fuse opens the circuit that is being protected. A slow melting feature enables many fuses to withstand momentary surges of excessive current. In this type of fuse, the fuse link is thickly constructed except at one or two portions of its length. The thick sections of fuse link absorb heat from the smaller, higher resistance sections and thus delay the melting for a small fraction of a second. Figure 148 shows a typical fuse and circuit breaker box.

96. Underload Protective Relay

a. Figure 149 shows an underload relay which disconnects the modulator when the r-f amplifier is underloaded. Compare this figure with that of figure 145 where the contacts normally are closed and are opened by a surge of excessive current. In figure 149 the contacts are normally open, and close only when current is adequate. The closing point of the contacts can be adjusted by changing the setting of the adjustable resistor, *R*, which is in parallel with the coil.

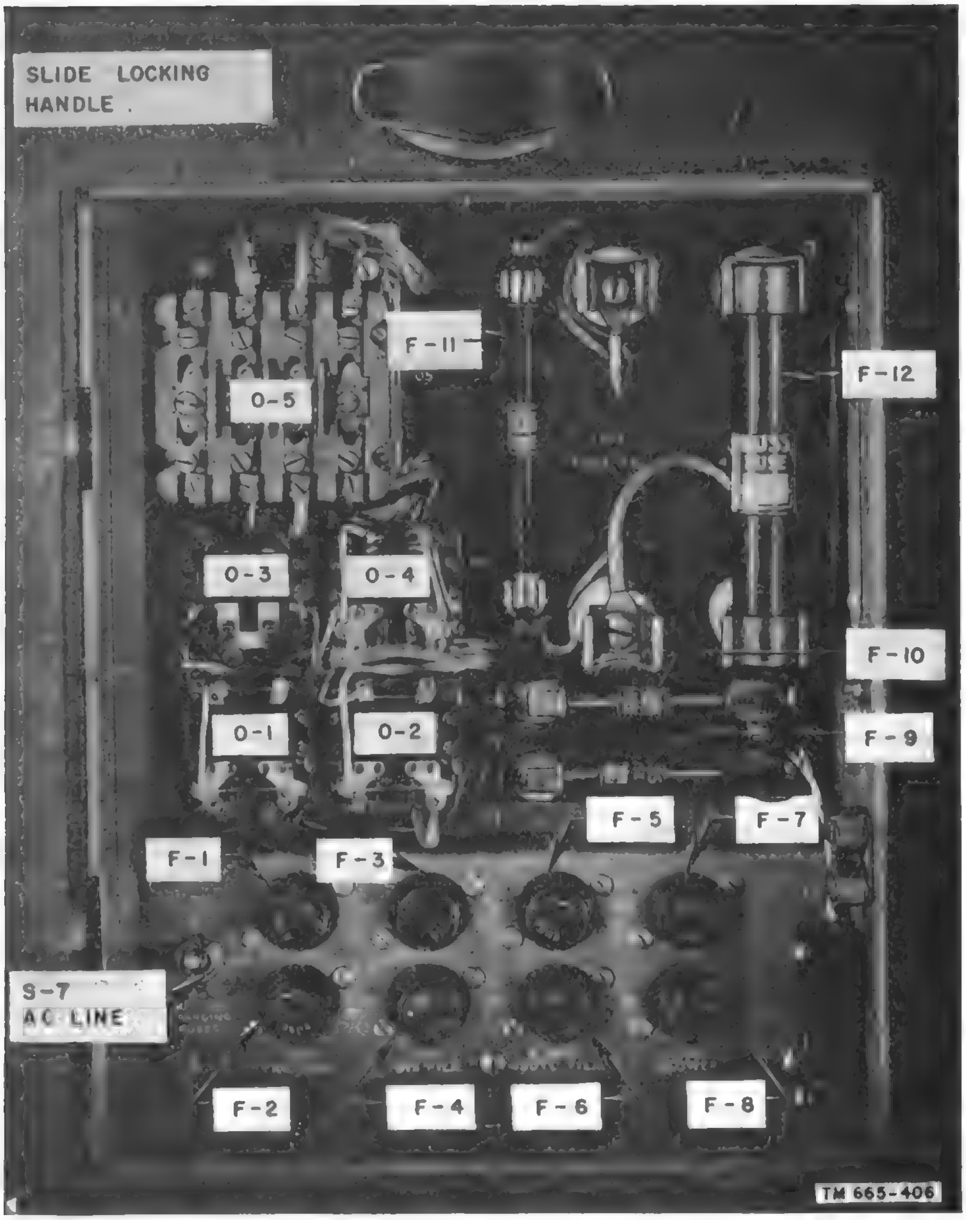


Figure 148. Typical fuse and circuit breaker box.

b. The relay of figure 149 does not have to be reset by the operator. Whenever current through the underload coil rises again to normal value after it has been tripped, the contacts close again by themselves. However, if the current fluctuates around the normal value, chattering (consistent opening and closing) occurs. The relay of figure 145 cannot chatter because of the mechanical latch, but it must be reset by the operator.

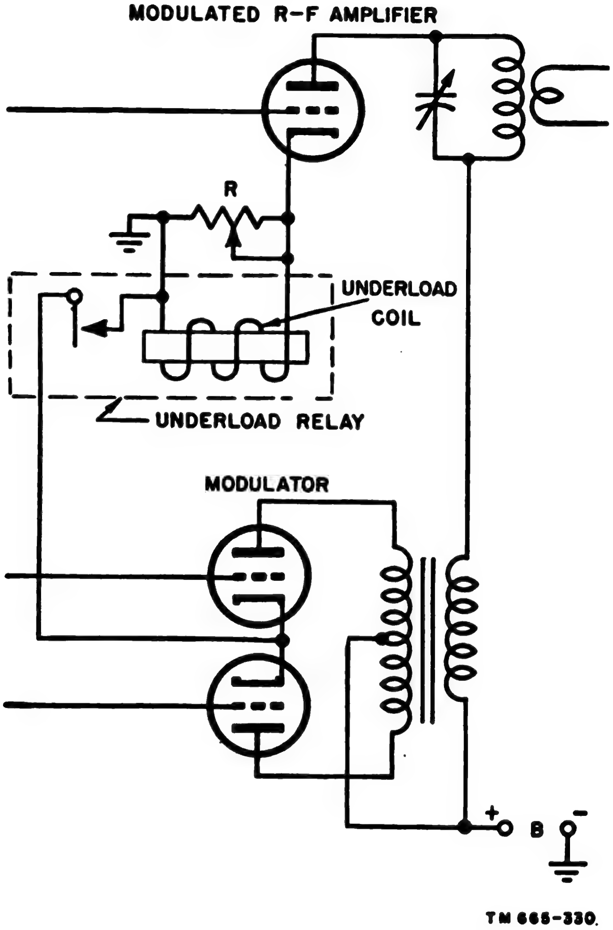


Figure 149. Circuit using an underload relay.

97. Time Delay Relays

a. It has been explained previously that slow operating relays are capable of introducing a delay of about a fraction of a second. Longer delays are often needed, for which purpose, time delay relays are used. Figure 150 shows a thermostat type time delay relay circuit. This circuit is used to delay the application of high voltage to the plates of certain tubes until their filaments have reached proper operating temperature. With the time delay relay inactive, its armature falls against the lower set of contacts and closes the relay heater circuit. The result is that the heater element with its series limiting resistor is placed directly across the a-c input line. Current flows through this circuit and heats the bimetallic strips when the a-c input switch is closed. After a preset time interval, the bimetallic strips bend sufficiently to close the contacts at point C. The closed contacts cause the relay coil circuit to be completed across the a-c input line permitting current to flow. The armature is pulled away from the lower contacts and closes the upper contacts with the relay coil energized. When the high-voltage relay switch is closed, the high-voltage relay coil is then connected across the input line and the relay is activated, thereby closing the primary circuit of the high-voltage transformer. The closing of the time delay relay opens the heater circuit and permits the heater to cool, returning the bimetallic strip to its normal position. The contacts at C open as the heater element cools, but the upper set of contacts on the time delay relay serve as holding contacts to keep the coils of both relays energized, thereby applying voltage to the high-voltage transformer. The length of the time delay that is obtained is determined by the type of bimetallic element used and the type of heating coil that actuates it.

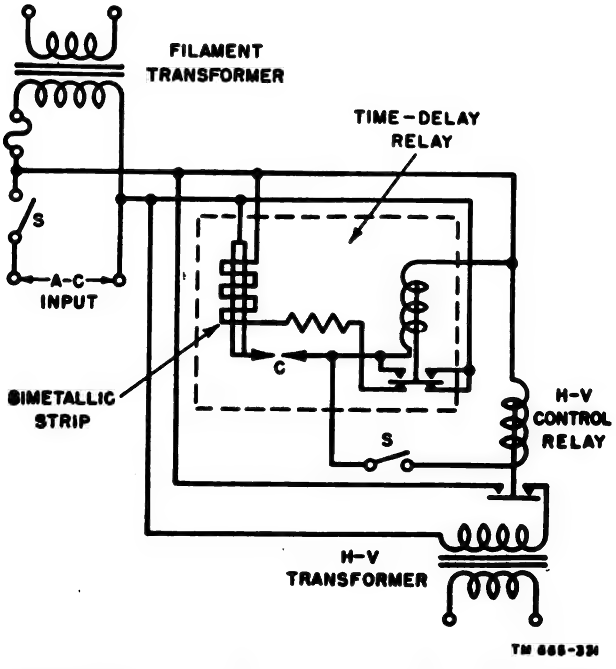


Figure 150. Use of thermal type time delay relay in high-voltage circuit.

b. Figure 151 shows a motor driven time delay relay. A small synchronous motor drives a gear train that has a set of adjustable contacts on the last gear. The circuit is closed when this set of contacts is turned until they touch the stationary contacts. Another type of motor driven relay uses a spring action to close the relay contacts. The spring is released by the gear train after a given time interval.

c. In still other types of time-delay relays, the armature acts as a piston and forces oil, air, or vapor through a small opening. The pressure of the liquid or air holds back the armature and prevents it from closing the contacts. As the air or liquid gradually escapes through the opening, its pressure decreases and eventually the armature is enabled to move far enough to close the contacts. The size of the opening, in nature and viscosity of the fluid, and the force applied to the armature, together determine the period of the time delay.

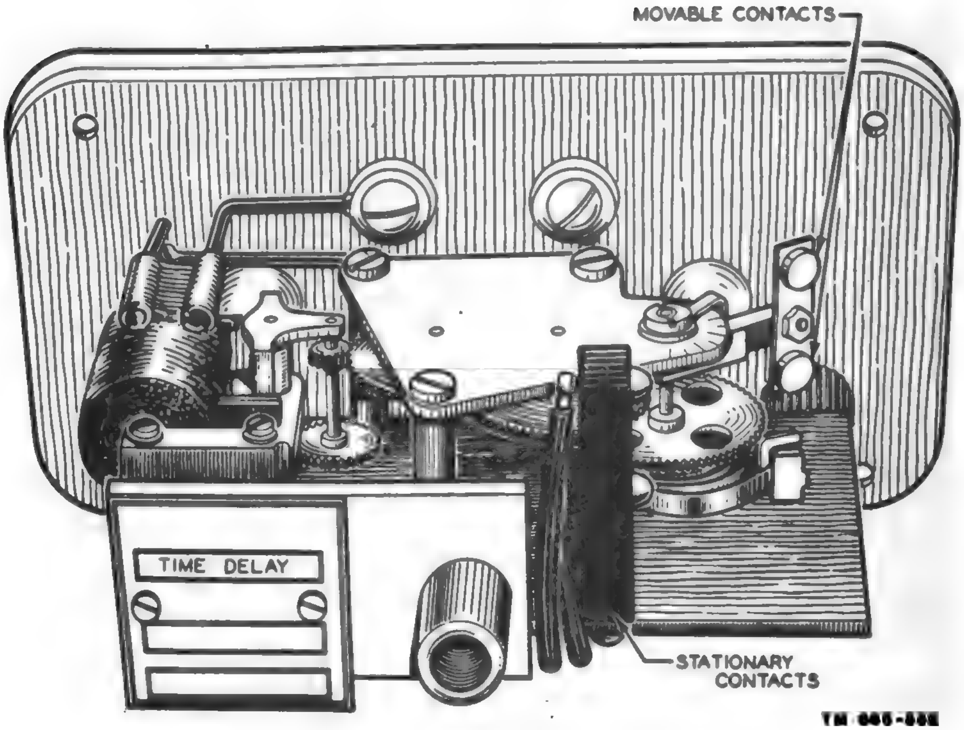


Figure 151. Motor driven time delay relay.

98. Door Interlock Switches

a. Protection of personnel from high voltages existing in transmitters is obtained by using *door interlock* switches. These switches automatically turn off the high voltages in the event that a door or panel of the transmitter is opened which places a high-voltage circuit within reach of the operator.

b. Door interlocks are switches which have open contacts when a door or panel is open and have closed contacts when a door or panel is closed. A common type of interlock consists of a small single-throw switch (plunger type) which normally is held open by a spring and is closed when the plunger is depressed. These switches usually are mounted in the transmitter cabinet behind doors and panels in such a manner that the plunger is depressed when the doors or panels are closed. Usually there are a number of interlock switches connected in series so that opening any door or panel breaks a circuit and turns off all high voltages which may endanger the operator.

c. A second type of door interlock consists of a female socket mounted on the transmitter cabinet and a matching plug mounted on the door or panel. The contacts on the plug are connected to the high-voltage circuits in the transmitter. When the covers are closed, the male and female connectors mesh and complete the circuit.

99. Auxiliary Circuits

Auxiliary circuits are used for a large number of purposes, some of which are indicated below.

A slow releasing relay often is used for remote control of c-w transmitters. The slow release relay remains closed as long as dots and dashes are transmitted, but opens when transmission is interrupted. The first dot or dash sent thereafter closes the relay again. The polar relay in figure 143 often is used for remote control of transmitter circuits. An overload relay (fig. 144) is used to protect an amplifier by opening the primary power supply whenever the plate current rises to an excessive value. In figure 149 the underload relay contacts do not close until the r-f amplifier is drawing sufficient current to provide a reasonable load for the modulator. Any circuit failure or maladjustment that reduces the plate current below a predetermined value reopens the contacts and interrupts the modulator B-plus line. In figure 150, switch *S* in series with the coil of the high-voltage relay may be part of a send-receive switch, or a set of contacts on a send-receive relay when using c-w. The circuit breaker of figure 147, which can tolerate temporary overloads without opening because of the heating time required to bend its bimetallic strip, often is used to protect motors or dynamotors that have large starting currents for a short period of time. Time delay relays are used to control the application of plate voltage to large size transmitting or rectifying tubes. They keep the plate circuit open until the tubes have had time to warm up.

a. Control Circuit. A push button circuit (fig. 152) provides control of a high-voltage power supply. Relay coil 1 is not energized until relay 2, which completes the interlock and filament circuits, is closed. With relay 2 closed, relay 1 can be closed by depressing the START button momentarily. The lowest set of contacts on relay 1 are are the holding contacts. After the START button is released, the energizing current for the coil of relay 1 takes the path through the closed STOP button, the holding contacts, and through the relay coil to the other side of the input power line.

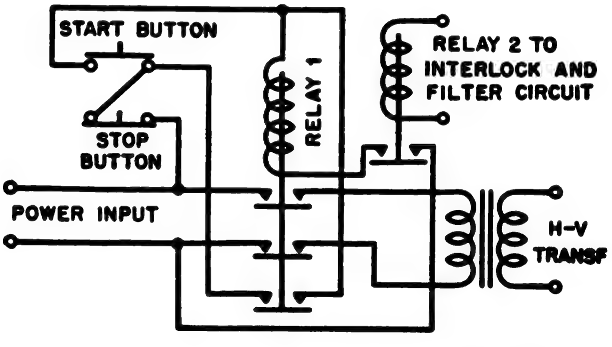


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Figure 152. Push button operated relay circuits.

b. Protective Circuit. In the typical auxiliary circuit for protection of personnel shown in figure 153, high voltage cannot be applied to the transmitter equipment if their protective covers are not properly in place. If any cover is removed, the high-voltage line opens. Door and panel interlock switches mechanically associated with the protective covers are in series with the primary of the power transformer. If one of them is open, the return from the transformer primary to the power line is open, and the coil of the high-voltage transformer control relay cannot be energized. When that relay is energized, high voltage can be applied to the transmitter by closing the switch in series with the primary side of the high-voltage transformer. In practice, this switch may consist of contacts on a push button operated relay like that shown in figure 152.

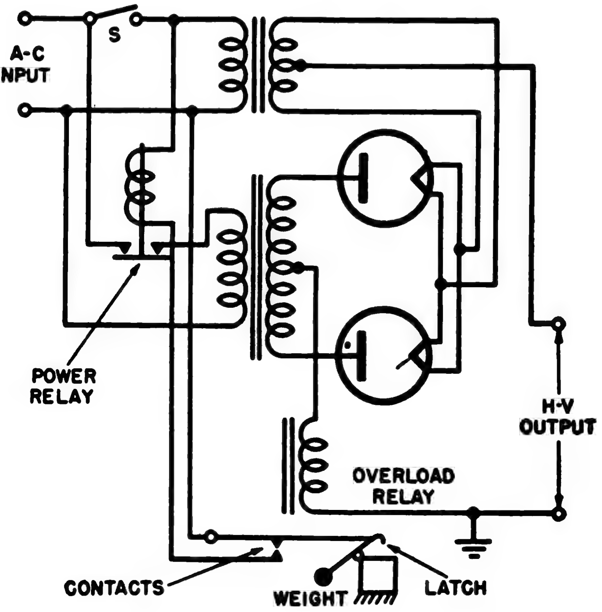

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Figure 153. Typical interlock circuits for high-voltage supply.

100. Summary

a. Control circuits generally are designed for the protection of the equipment and operating personnel.

b. Control devices for operator safety include door and panel interlock switches.

c. Transmitters are protected against damage by overload and underload relays and by interlocking controls which must be operated in a definite sequence before the transmitter can be put into operation.

d. A relay is a switch operated by electromagnetic action. The basic parts are a coil, a core, an armature, and contacts.

e. Slow release relays have a shorted turn or a heavy copper slug on the heel end of the core which slows down the decay of the magnetic field of the core when current stops flowing through it.

f. Slow operating relays have the shorted turn or slug on the armature end of the core. The build-up of the magnetic field is retarded by preventing the armature from pulling in almost instantly after the application of the exciting voltage.

g. Overload relays are designed to open a circuit when current in excess of a predetermined value flows through its coil.

h. Underload relays open a circuit or prevent it from closing when the current through the coil is appreciably less than a predetermined value.

i. Time delay relays are relays which include a thermal or clockwork mechanism to provide a definite interval between two switching operations.

j. Circuit breakers are special switches with thermal or electromagnetic control to open the circuit when the current through it exceeds a desired value.

k. Fuses are fusible metal links which are inserted in series with the circuit to be protected.

l. Push button controlled circuits are used in conjunction with circuit control relays and contactors to provide simplified transmitter control.

m. High-power transmitters have door and panel interlock switches to protect personnel against extremely high voltages.

101. Review Questions

a. What are the three functions of an auxiliary circuit?

b. Explain the basic operation of a relay.

c. What is the difference between slow operating and slow release relays?

d. What is the difference between a control relay and a contactor?

e. Describe the operation of a thermal type circuit breaker.

f. Describe the operation of a thermal type time delay.

g. Draw a diagram illustrating a simple push button operated control circuit.

CHAPTER 7

RADIO RECEPTION

102. Reception

Receivers perform the function of intercepting a tiny part of the radio-wave energy radiated by transmitters and of recovering the information contained in it. This information can be in the form of radiotelegraphy code signals, consisting of periodic interruptions of the radio-frequency carrier, or in the form of modulation of the amplitude or some other characteristic of the r-f carrier. Only receivers for continuous waves and for amplitude modulation are discussed here. Both types must contain the necessary circuits for performing the following six functions (fig. 154): signal reception, signal selection, r-f amplification, detection, a-f amplification, sound reproduction. These are sufficient for a-m reception, but for c-w reception an additional circuit in the form of a beat-frequency oscillator is required.

a. Signal Interception. The *receiving antenna* intercepts a small portion of the passing radio waves. The signal power extracted by ordinary receiving antennas is only a few microwatts, which is sufficient for subsequent amplification as long as the noise energy intercepted by the antenna is substantially less than this.

b. Signal Selection. The physical dimensions of the antenna generally favor its response for a specific frequency band within the total radio-frequency spectrum. Within this given frequency band, some means must be provided to select the desired signal from all of the r-f carriers intercepted by the antenna. Signal selection is achieved by tuned I-C (inductance-capacitance). These respond best at their resonant frequency, as explained previously, and respond very little or not at all at other frequencies. Several tuned circuits

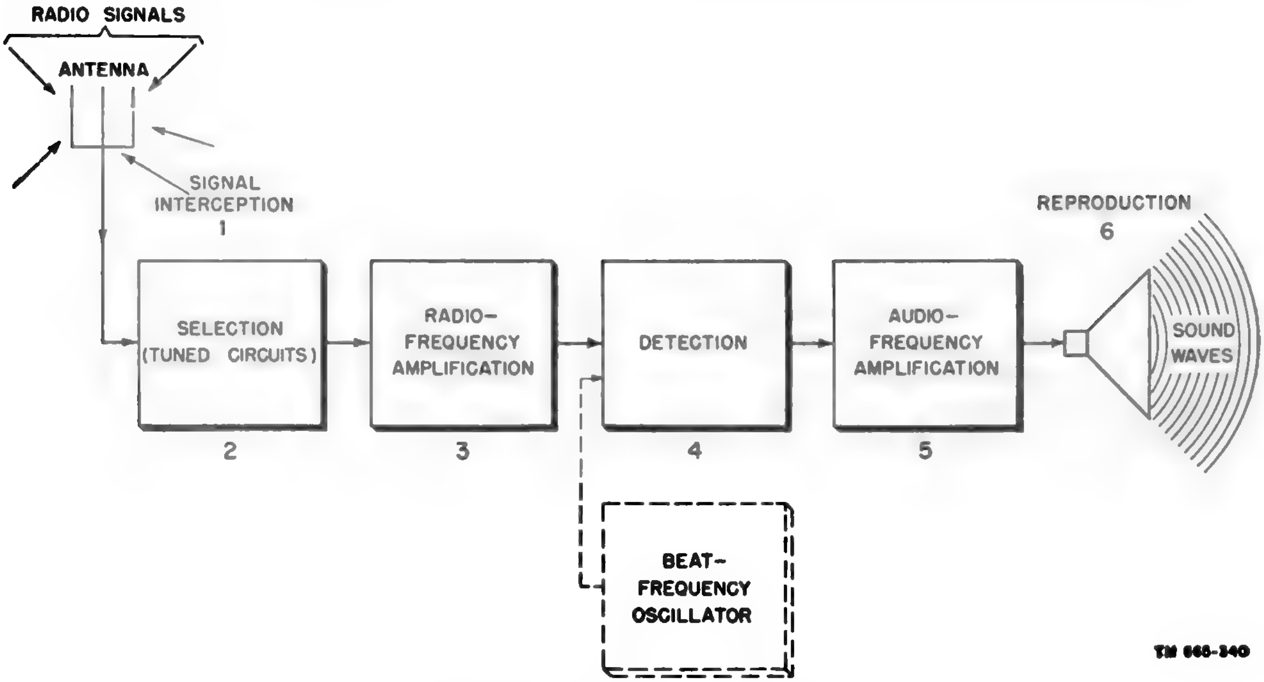

Figure 154. Essentials of radio reception.

usually are necessary to differentiate sufficiently between the desired signal frequency and all other frequencies.

c. R-F Amplification. The weak signals intercepted by the antenna usually must be amplified considerably before the intelligence contained in them can be recovered. One or more r-f amplifiers serve to increase the signal to the required level. A selective tuned circuit in the input of each r-f amplifier makes sure that only the desired signal is amplified. If amplification is carired out only at the carrier frequency of the signal, the receiving system is known as a trf (tuned radio-frequency) receiver.

d. Detection (Demodulation).

(1) If the signal is amplitude-modulated, the original intelligence must be recovered from it by separating the modulation signal from the r-f carrier. The circuit which separates the audio-frequency signal variations from the r-f carrier is called the *detector* or *demodulator.* Most detectors do not operate well at very low signal levels, and this is one of the reasons why radio-frequency amplification usually is required ahead of the detector.

(2) In the case of c-w (radiotelegraphy) reception, a beat-frequency oscillator is used in the receiver circuit (shown by dotted lines in figure 154). The bfo provides an r-f signal which *beats* or *heterodynes* against the frequency that is injected into the detector. The resultant frequency is an audio frequency which can be heard in the headset or loudspeaker at the output of the receiver. In some cases, the bfo is combined with the detector stage.

e. A-F Amplification. The signal frequency present in the output of the detector stage generally is too weak to operate a headset or loudspeaker. Therefore, one or more stages of audio-frequency amplification are required to strengthen the audio output of the detector to a level sufficient to operate the headset or loudspeaker.

f. Sound Reproduction. The amplified audio-frequency signal is applied to an electromechanical reproducing device, such as a loudspeaker or headset, which translates the electrical audio-frequency variations into corresponding sound waves. For a-m, the sound output of the reproducer is a close replica of the original audio tones at the transmitter. For c-w, the sound output is a tone the frequency of which depends upon the frequency of the local oscillator. This tone is heard whenever the key is depressed at the transmitter, and, consequently, it reproduces the interruptions of the radio carrier in accordance with the telegraphic code.

103. Types of Receivers

a. In the development of radio, the circuits and components necessary to perform all of the functions outlined above came into existence gradually. In the early days of radio, little was known about antennas, tuning, and amplification. A *receiver* in the early 1900's, for example, consisted of a very inefficient detector and a telephone headset. Such a receiver could be used only at a very short distance from the transmitter and did not permit selection of transmitted signals. Years later, the range of reception was considerably increased by the addition of the elevated antenna and the ground connection, resonant tuning circuits, and the discovery of the more sensitive crystal detector.

b. The invention of the triode vacuum tube by Lee de Forest made possible the development of simple *triode detector receivers* having increased sensitivity and stability over the crystal set. Various refinements were made to increase the amplification and hence the sensitivity of the simple one tube receiver. The most important among these was the invention of the regenerative and the superregenerative detector circuits by Armstrong. These will be discussed later. Although these detectors were highly sensitive, they were none too stable and had poor fidelity. The regenerative detector still is used for the detection of c-w, and the superregenerative detector for voice signals. It was found that a-m reception could be improved substantially by adding separate stages of tuned radio-frequency amplification and audio-frequency amplification to the simple triode detector. These trf receivers have excellent fidelity and fairly good sensitivity and consequently are still used in many applications to this day. However, unless many tuned circuits are used, the trf receiver does not have good selectivity. Selectivity is the ability to differentiate between desired and unwanted signals.

c. The invention of the superheterodyne receiver by Armstrong, during World War I, removed the chief deficiencies of the trf receiver. Superheterodyne receivers are in almost universal use at the present time because they have excellent sensitivity, selectivity, and fidelity (ch. 8). In this receiver, signal amplification is carried on in steps, partly at the carrier frequency and partly at a lower intermediate frequency to which the received signal is converted.

104. Simple Crystal Receiver

a. Circuit. In the elementary type of crystal receiver shown in A of figure 155 the basic parts are an antenna, a tuned *L-C* tank circuit, a crystal which is the detector, and a headset bypassed by capacitor C_b. The signal intercepted by the antenna is coupled to the *L-C* circuit through the r-f transformer, *T*. If a step-up ratio is used between the primary antenna winding and the secondary tank coil winding, some amplification exists. Certain mineral crystals, such as galena, silicon, and carborundum, have the property of allowing current to flow through them much more readily in one direction than in the opposite direction. Therefore, they act as rectifiers of alternating current. Galena crystals are used in most crystal receivers. The headset serves to translate the audio-frequency variations in its input to corresponding sound waves. C_b is an r-f bypass capacitor to keep radio-frequency currents out of the headset.

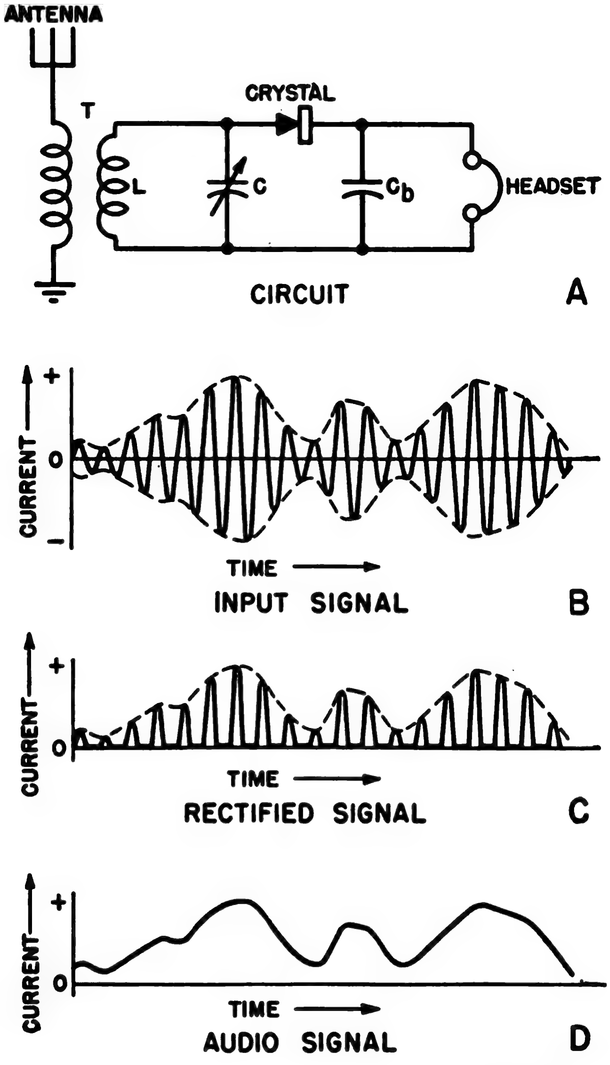

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Figure 155. Crystal receiver and waveshapes.

b. Operation. Assume that the *L-C* tank circuit is tuned to one of the modulated radio-frequency signals intercepted by the antenna. The initially weak signal is coupled to the resonant tank circuit through the r-f transformer, being slightly stepped up in the process. The still small signal current is considerably amplified by the principle of resonance. The tank circuit strengthens the r-f current of the frequency to which it is tuned, while discriminating against r-f currents of all other frequencies. The ability of the tank to select just one frequency depends on the sharpness of resonance, which in turn is determined by the losses in the tank circuit. B shows the modulated r-f signal selected by the tank circuit. This signal oscillates at a rate determined by the carrier frequency. The strength or amplitude of the signal varies at an audio rate determined by the modulating signal frequency. The headphones are incapable of responding to the extremely rapid carrier-frequency oscillations, but they can reproduce the slower audio-frequency variations of the modulation, which contain the intelligence. Consequently, it becomes necessary to separate the modulating signal frequencies from the r-f carrier. This process is carried out in two steps.

(1) The first step in the *rectification* of the r-f carrier by means of the crystal. Since the crystal can respond only to current flowing in one direction, it eliminates the negative portions of the modulating signal and carrier below the zero axis. The resulting wave-form is shown in C of figure 155. The current through the circuit never reverses in polarity, but it still pulsates at the rate of the r-f carrier. It is necessary to smooth out these pulsations before the modulation can be re-

produced by the headset, since the headset cannot respond to radio frequencies.

(2) The second step is the smoothing or *filtering action* achieved with the bypass capacitor, C_b. The value of this capacitor is so chosen that it has a low reactance at radio frequencies an da relatively high reactance at audio frequencies. As a result, the r-f is shunted around the headset, and the audio-frequency variations of the carrier pass through it. In C, the current is passing through C_b and in D the current is passing through the headset. The audio reproduced as sound by the headset corresponds to the original audio at the transmitter.

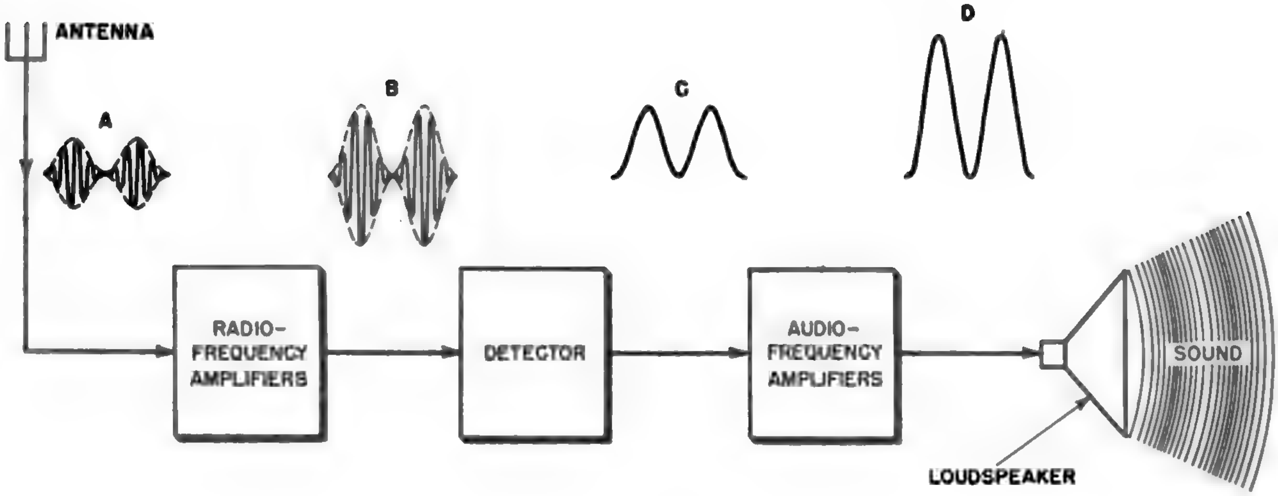

Figure 156. Block diagram of trf receiver.

105. Tuned Radio-Frequency Receiver

The tuned radio-frequency receiver shown in figure 156 consists of one or more stages of r-f amplification with tuned circuits in the input of each stage, a detector stage, and one or more stages of audio amplification, driving a loudspeaker. The inputs and outputs of each stage are shown in the block diagram. The signal intercepted by the antenna is portrayed as an r-f carrier modulated by two cycles of an audio-frequency tone (waveshape A). It is selected and amplified by the trf amplifiers. The amplified output (waveshape B) is applied to the detector stage, where it is detected. The output of the detector which is shown as waveshape C consists only of the audio-frequency variation of the carrier. The a-f signal is strengthened by one or more stages of audio amplification until its amplitude is of sufficient value to drive the loudspeaker, as in waveshape D.

106. Tuned R-F Amplifiers

a. Operation. In figure 157, the signal input from the antenna or a preceding r-f amplifier is coupled to the tuned-grid tank circuit through r-f transformer $T1$. The tank circuit augments the input signal frequency to which it is tuned by $C1$, but at least partially suppresses all other frequencies. The signal selected by the $L1C1$ tank circuit is applied to the control grid of tube $V1$ and appears amplified in the plate circuit of the tube. Although a triode is shown for illustration, pentodes commonly are used. The output of $V1$ is coupled through transformer $T2$ to the input of the next stage, which can be another r-f amplifier or the detector. $L2C2$ is tuned to the same frequency as $L1C1$ for a maximum transfer of energy from $V1$ stage to the next stage. R-f amplifiers in receivers are operated class A so that they present a minimum of distortion to the modulated signal. Resistor $R1$ in the cathode circuit of the tube provides the required negative bias for class A operation. The r-f is bypassed around the bias resistor by capacitor $C3$, which is in parallel with it.

b. Selectivity.

(1) It has been pointed out that the reason for using a tuned tank circuit in an r-f

amplifier is its ability to differentiate between the desired signal frequency and undesired frequencies, whether they are unwanted signals, noise, or other disturbances. The extent to which a receiver has this ability is called *selectivity*. The greater the number of tuned circuits in a receiver, the greater is its overall selectivity. The selectivity of each individual tuned circuit is determined by the sharpness of its resonance. The sharpness of resonance, in turn, depends on the resistive losses in the tank circuit, or equivalently, on its effective Q.

(2) A of figure 158, shows resonance curves of a typical tuned circuit for various values of Q. When the Q is low (graph for $Q=50$), the gain or response of the circuit is broad, as indicated by the wide resonance peak. Since the relative reponse falls off very slowly when the circuit is detuned from resonance in either direction, it cannot discriminate well between the desired resonance frequency and unwanted (off-resonance) frequencies. Therefore, the selectivity is poor. For $Q=100$, the resonance peak is much sharper, and the selectivity is considerably improved. For a Q of 150, the resonance curve is very narrow and the selectivity is excellent. In addition, this high value of Q increases the relative voltage gain of the tuned circuit at resonance.

(3) To illustrate the effect of tank circuit Q on the selectivity of each stage, consider two signal voltages of equal strength, which are intercepted by the antenna and applied to the grid tank circuit of the first r-f stage. The tank is tuned to the desired signal frequency of 1,000 kc. The frequency of the unwanted signal is 980 kc, as shown in A. For a $Q=150$, the relative gain of the tank for the desired 1,000-kc signal is arbitrarily taken as 100. The unwanted 980-kc signal is -20 kc off resonance, and the corresponding relative response of the tank is seen to be 20. Therefore, at the output of the tank the relative gain of the 980-kc signal is only $20/100=1/5$, or 20 percent of the gain of the desired 1,000-kc signal. However, if tank circuit Q is only 50, the relative voltage response of the 1,000-kc signal is 35, and that of the 980-kc signal is about 20. Consequently, the relative response of the undesired 980-kc signal in this case is $20/35=4/7$ or about 57 percent of that of the desired 1,000-kc signal. An unwanted signal more than one-half as strong as the desired signal would be very disturbing at the output of the receiver. Therefore, a high-Q tank circuit in each stage of the receiver is essential for selectivity.

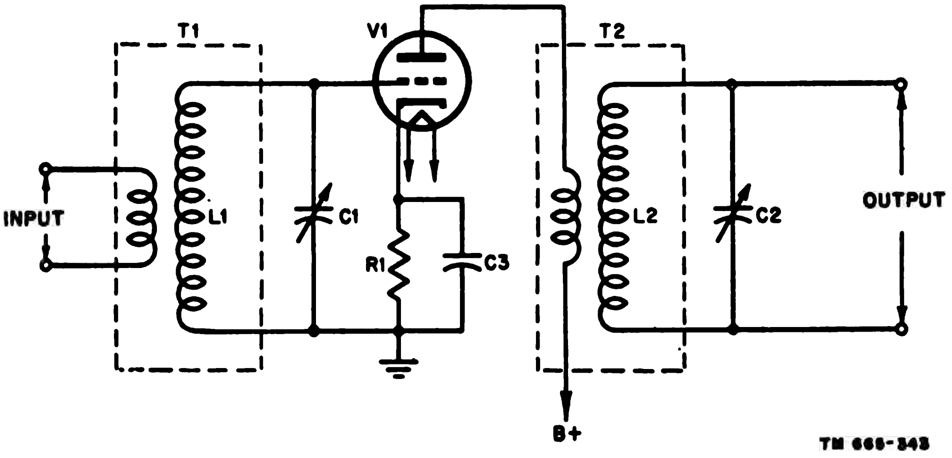

Figure 157. Tuned r-f stage of trf receiver.

(4) The over-all selectivity of a receiver can be increased greatly over that of a single stage by *cascading* (putting in series) a

number of tuned r-f amplifier stages. The greater the number of r-f stages, the greater the number of tank circuits. The manner in which the selectivity of a receiver goes up in direct proportion to the number of tuned r-f circuits used is illustrated in B. The following is the result when a 1,000-kc signal and a 980-kc signal of equal strength are applied to the input of the resonant grid tank circuit of the first r-f amplifier in a receiver. To emphasize the effect of many tuned stages, broad tuning low-*Q* tank circuits have been chosen for plotting B. The output of the first tuned circuit for the 980-kc signal is 50 percent or one-half of that for the desired 1,000-kc signal. The ratio of the desired signal (1,000-kc) to the undesired signal (980-kc), therefore, is 2 to 1, after passing through the first tuned circuit.

(5) The first r-f tube amplifies these signals equally so that the ratio of the two voltages applied to the input tank circuit of the next stage is still 2 to 1. The ratio of the two signal voltages in the output tank circuit of the second stage is 2 times 2 to 1, or 4 to 1. The amplitude of the 980-kc signal, after passing through two tuned circuits, therefore, is one-fourth or 25 percent of that of the desired 1,000-kc signal, as in (B of fig. 158). If the signals are passed through another tuned stage of similar characteristics, the ratio of desired to undesired signal will be 2 times 4 to 1 or 8 to 1 in the output of the third tuned circuit. The amplitude of the 980-kc signal then will be one-eighth of

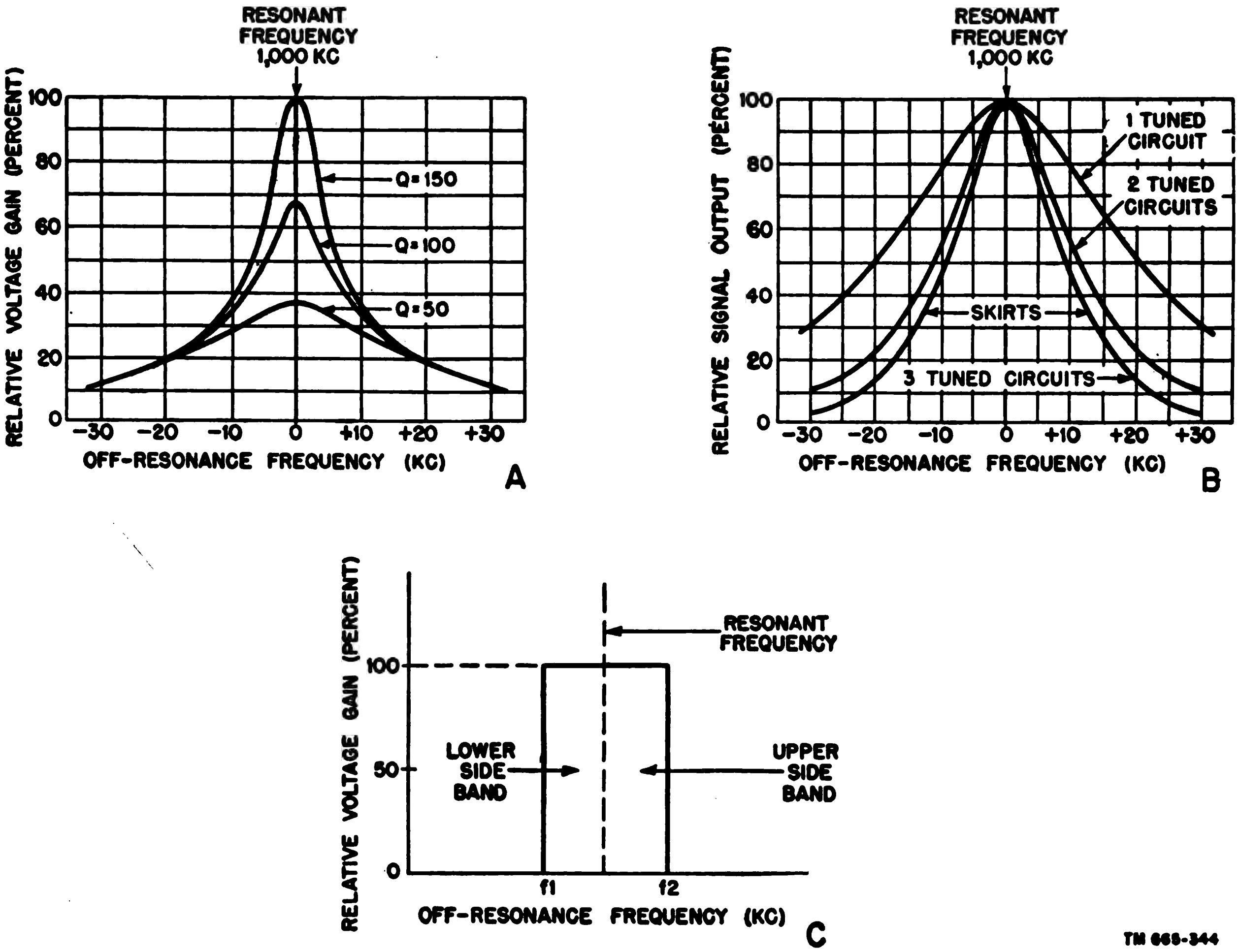

Figure 158. Selectivity of trf receiver.

12.5 percent of that of the 1,000-kc signal, as indicated. To make the 980-kc signal negligible compared to the desired 1,000-kc signal, a fourth tuned circuit is required, or else the Q of each individual stage must be improved. *Cascading* affects chiefly the *skirts* or sides of the resonance curve, but does not change materially the sharpness or *nose*.

c. Fidelity.

(1) The selectivity or sharpness of the resonance curve of an individual tuned circuit cannot be improved indefinitely by increasing the Q. If the resonance peak is made so sharp that it cuts off part of the upper and lower side bands of the modulated carrier, the bandwidth will be impaired and the signal becomes distorted. Since there are two side bands, the tuned circuit must pass a bandwidth twice that of the highest modulating frequency. Consequently, if an audio tone of 5,000 cps is to be passed, the bandwidth is 2 times 5,000=10,000 cps, or 10 kc. If the carrier is, say 1,000 kc, the tuned circuit must pass 5 kc on either side of its resonant frequency of 1,000 kc, or from 995 kc to 1,005 kc. Ideally, it should pass all frequencies within this 10-kc band with equal amplitude, while completely rejecting all frequencies outside of this band. This necessitates the *flat top* resonance curve shown in C. Frequencies $f1$ and $f2$ represent the lowest and highest frequencies of the resonance curve, respectively. Such a curve cannot be attained in practice, but it can be approximated through special *band-pass* circuits.

(2) The extent to which the tuned and other circuits of the receiver are capable of reproducing accurately all of the frequencies present in the input is known as *fidelity*. For c-w reception, side bands are confined within a very small region in the neighborhood of the carrier frequency, and fidelity is of no consequence. For c-w, therefore, the selectivity of the tuned circuits is made as great as possible. For radiotelephone service, a channel of 5 kc on each side of the carrier generally is sufficient, and the fidelity of the receiver is relatively unimportant. It is, however, of vital importance in a-m, and f-m, and television broadcast receivers, where relatively large bandwidths must be passed by each tuned circuit.

d. Sensitivity. The sensitivity of a receiver is defined as the minimum signal input voltage that will deliver a standard signal output power. This is a convenient definition, since the output power ordinarily is fixed by the type of receiver. Standard values varying from .05- to 1-watt output power are in use, depending on the type of receiver. The sensitivity usually is expressed in microvolts input to the antenna for the standard watt output. In addition to the definition of sensitivity as expressed in microvolts input for a standard output, a further quantity is specified in that the previous relation must exist for a given signal-to-noise ratio. The signal-to-noise ratio in itself is discussed below. The over-all voltage gain of the r-f and a-f amplifier stages determines directly the sensitivity achieved by a particular receiver. In a trf receiver, the number of tuned r-f stages is the most important factor contributing to the over-all gain.

e. Signal-To-Noise Ratio.

(1) It would seem that unlimited sensitivity could be obtained in a receiver by adding progressively more stages of amplification, and thus increasing the over-all gain almost indefinitely. Although more stages do give more gain, this is not the only factor determining the sensitivity, the other factor being *noise*.

(2) The term *noise* in radio reception applies to any form of undesired electrical disturbance occurring within the useful frequency band. The source of noise may be external or within the receiver itself. External noises are picked up by the antenna along with the desired signal, and both are equally amplified by the receiver, the noise tending to *mask* the signal. The most common externally produced noises are atmospheric disturbances and man-made interference. Atmospheric disturbances, often called *static*, are caused by electrical discharges which take place within the atmosphere, such as lightning and electrical storms.

(3) Man-made electrical noise can be caused by a great variety of electrical and electromechanical devices. Any device that produces electric sparks is a source of electromagnetic radiation, and, therefore, of noise. Common spark producers are electric bells, electric motors and generators, interruptors, and distributors and spark plugs in automobile engines. Direct radiators, such as diathermy machines, are another common cause of man-made interference. Most externally produced noises have the form of transient disturbances, called *impulses*. These vary in amplitude and their energy is distributed over an extremely wide range of frequencies. Impulse noise interferes directly with a-m reception at practically all useful frequencies of transmission. Special circuits are incorporated into communication receivers to eliminate or reduce at least a portion of externally produced impulse noise.

(4) Noise produced by the receiver itself results from three main causes: tube noise (also called *shot effect*), thermal agitation, and hum. Shot effect is generated within vacuum tubes by random fluctuations occurring in the electron flow from cathode to plate. These fluctuations are produced as a result of small variations in the rate of emission of electrons from the cathode, and they are independent of the signal at the grid. The fluctuations are amplified along with the useful signal and they result in a noise. Triodes, because of their simple structure, are always inherently less noisy than multigrid tubes such as pentodes. Shot effect can be minimized to some degree by operating the tube with a sufficiently high filament temperature to cause copious emission of electrons.

(5) *Thermal agitation* is a form of random noise caused by temperature differences between the terminals of resistors and other components. These differences produce random motions of the free electrons in the conductors or resistors, which are superimposed as additional noise currents upon the normal conduction current. The higher the resistance, the greater is the equivalent thermal noise voltage produced across its terminals. Proper placement of the components reduces these temperature differentials, and hence the thermal noise voltage.

(6) Resistor noise sometimes is a source of trouble. Certain composition resistors composed of carbon granules generate noise, often considerably in excess of thermal agitation noise, and when such resistors are discovered they must be removed from the circuit and replaced with an equivalent resistor which is not noisy.

(7) *Hum* often is present in a-c line-operated receivers, usually because of improperly filtered power supplies. Inductive stray pick-up from nearby coils and transformers also can produce hum. Proper filtering of the power supply, careful placement of the components, and shielding help to minimize hum.

(8) Noise is particularly troublesome when produced in the *input* stage of the receiver, which consists of the antenna, the coupling circuit, and the first r-f amplifier tube. This noise generated is subject to the full amplification of the receiver, and thus tends to mask the received signal. This imposes a limit upon the weakest signal which can still be received. Noise voltages contributed by subsequent stages of the receiver are of minor importance compared with that produced in the input stage.

(9) It is not the absolute value of the signal strength at the input of a receiver, therefore, that determines the usable sensitivity, but rather the ratio of that signal strength to the strength of all interfering noise (internal and external) that appears along with the signal. This ratio of signal strength to noise at the input of a receiver is called the *signal-to-noise ratio*. It is this ratio that limits the maximum sensitivity of a receiver. Since noise is distributed more or less uniformly over the entire frequency spectrum, the signal-to-noise ratio is dependent on the bandwidth which must be passed by the receiver. The signal-to-

noise ratio is improved when the bandwidth is cut down to the minimum necessary for acceptable intelligibility.

f. Reradiation Suppression. Another important function of the r-f amplifier stage in receivers is the suppression of radiation of electromagnetic energy occurring in subsequent stages of the receiver. It will be seen later that the regenerative detector circuits frequently used in trf receivers are capable of radiating appreciable energy. If such an oscillating detector were connected directly to the antenna in the input of the receiver, it would radiate a fairly strong signal via the antenna which acts as its load. With the r-f stage interposed between the antenna and detector, this cannot happen, and the stage functions as an *isolating* or *buffer* amplifier. Direct radiation from the oscillating detector is prevented further by shielding the entire receiver.

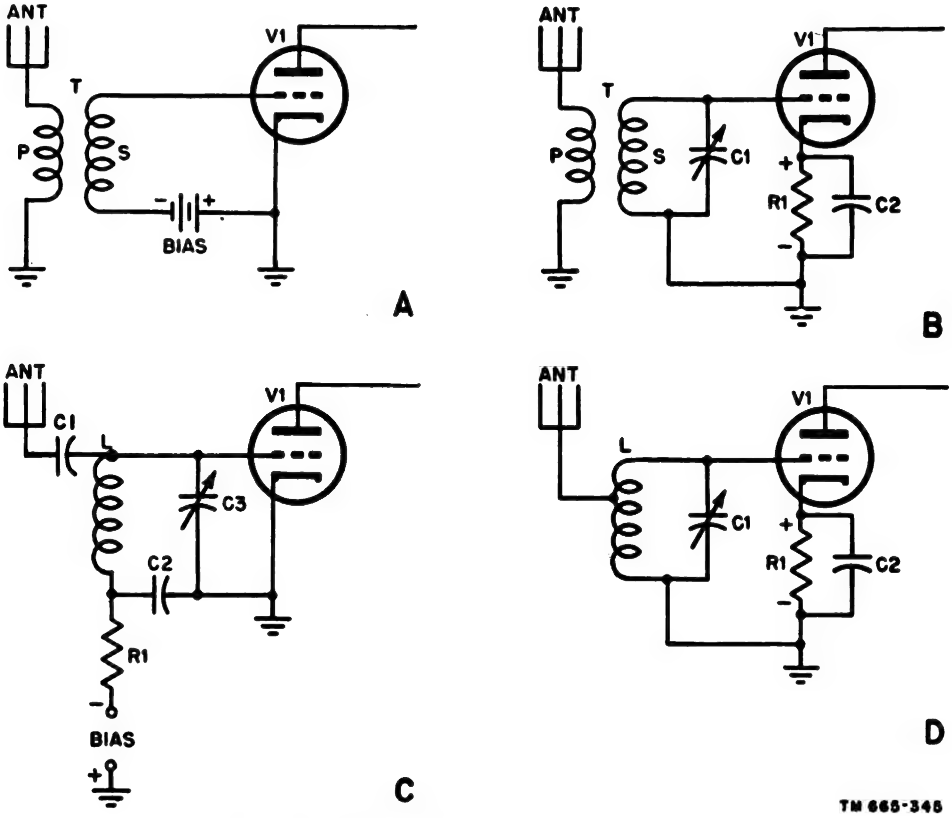

Figure 159. Typical antenna-coupling circuits.

107. Antenna Coupling

. The antenna-coupling system (fig. 159) transfers the signal intercepted by the antenna to the grid of the first amplifier tube in the receiver. Since the antenna input in general has a low impedance, and the grid circuit of the amplifier tube has a very high impedance, the antenna-coupling system serves also as an impedance-matching device to produce efficient energy transfer.

a. An *untuned* transformer-coupling arrangement is shown in A of figure 159. This arrangement, if properly designed, has a fairly good frequency response over the entire frequency range of the receiver. However, compared with the tuned r-f transformer, it has poor selectivity and considerably less sensitivity. Resistance-capacitance coupling is used occasionally, instead of the transformer, T, with a consequent improvement in uniform response of the receiver over the frequency range.

b. By far the most common antenna-coupling arrangement is the conventional tuned r-f transformer, shown in B. The secondary windings of transformer *T* are tuned to the desired signal frequency with variable capacitor *C*1, whereas the primary usually is untuned. Because of circuit resonance, this results in improved selectivity and sensitivity. In addition, a voltage step-up of approximately 6 to 8 is possible between the primary and secondary coil of the transformer. The bias voltage for *V*1 is developed across resistor *R*1. *C*2 is an r-f bypass capacitor.

c. If the signal intercepted by the antenna is weak, greater coupling may be desirable between the antenna and grid. This can be accomplished by the capacitive and direct input coupling arrangements shown in C and D, respectively. In C, the amount of coupling between the antenna and the tank circuit is determined by the ratio of the reactances of coupling capacitors *C*1 and *C*2, which form an a-c voltage divider. In D, the same result is achieved by connecting the antenna directly to a tap on tank circuit coil L. Although having good sensitivity, both circuits have poor selectivity. Another variation of direct coupling is the *loop antenna*, which is sometimes used because of its directional effect. Here, a coil of wire making up a loop comprises the inductance of the first tuned circuit in the receiver.

108. Interstage Coupling

Three basic types of coupling are in use between r-f amplifier stages—transformer coupling, impedance coupling, and resistance-capacitance coupling (fig. 160).

a. The conventional transformer-coupled circuit is illustrated in A; this is the most widely used arrangement. The untuned primary of transformer *T* in the plate circuit of *V*1 is coupled to its tuned secondary in the grid circuit of the next r-f stage, *V*2. The information given concerning the voltage step-up and selectivity of the tuned transformer-coupled antenna arrangement, in B, applies here also. Transformer coupling is the sim-

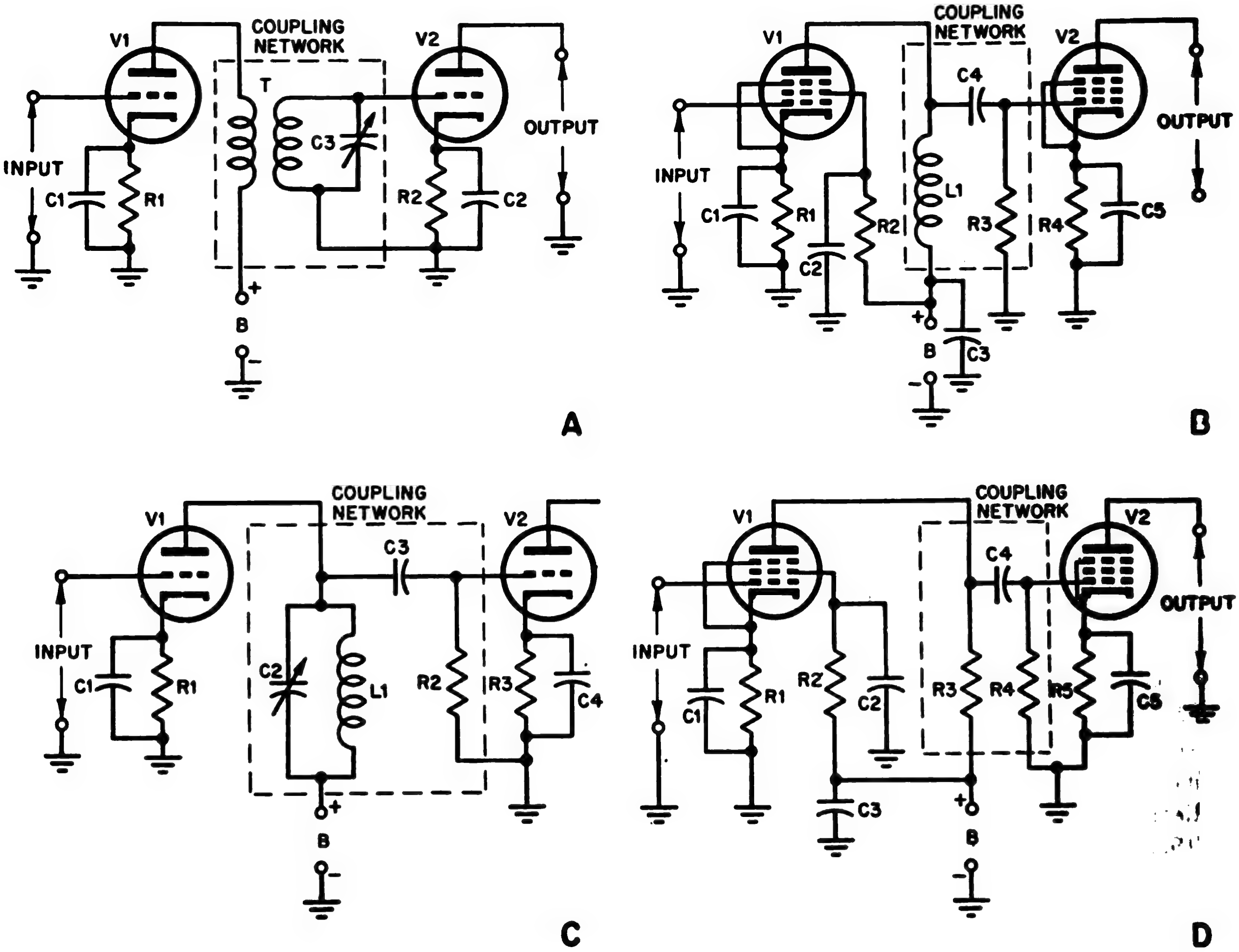

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Figure 160. Interstage coupling circuits.

plest, and, in general, the most satisfactory arrangement.

b. Impedance coupling is used occasionally between r-f amplifier tubes, especially with pentodes. In B, *L*1 represents an r-f choke which is the plate load of *V*1. The voltage developed across *L*1 is coupled through capacitor *C*4 to the grid input resistance *R*3 of the next stage, *V*2. Since *L*1 is untuned, the gain of the stages should be fairly uniform over the entire tuning range of the receiver. In practice, uniform amplification cannot be achieved, since the choke resonates at some frequency with the distributed capacitance of the coil and the input capacitance of *V*2. The result is a reduction in gain above and below the resonant frequency of the choke. In the tuned impedance coupling circuit, in C, the tuned circuit, *C*2*L*1, is the plate load of amplifier *V*1. Maximum signal voltage is developed across the load when *C*2 is adjusted so that the tank circuit resonates at the frequency of the desired signal. This signal voltage is coupled to the grid of *V*2 through coupling capacitor *C*3 which has a low reactance to the signal frequency but blocks the d-c. The grid signal voltage of *V*2 is developed across input resistor *R*2. In some practical examples, a fixed tuning capacitor is used for *C*2, and tuning is accomplished by a molded iron dust magnetic core which can be moved in and out of coil *L*1. This method is known as *permeability* or *slug tuning.* Excellent *Q*'s for the tank circuit can be obtained even at fairly high frequencies with specially developed iron-dust magnetic cores. Permeability tuning often is used in connection with push button fixed-channel tuning.

c. An untuned resistance-capacitance coupled circuit is shown in D. Pentodes are used instead of triodes to produce a large voltage gain. The signal variations at the output of *V*1 are reproduced across the plate load resistor *R*3. This signal voltage is coupled to the grid of *V*2 through coupling capacitor *C*4 which also blocks the d-c voltage from the grid of *V*2. The grid return circuit of *V*2 is completed through *R*4. A resistance-coupled stage sometimes is incorporated into a trf receiver as an inexpensive means of boosting amplification.

109. Shielding

a. The necessity for shielding certain parts of a receiver to prevent radiation has been discussed above (par. 106*f*). An even more important function of shielding is to prevent regenerative feedback of energy and parasitic oscillation. Feedback and possible oscillations can occur because of stray electromagnetic and electrostatic fields generated by a circuit operating at a relatively high signal level. These may be coupled to a circuit tuned to the same frequency operating at a low signal level in the proper phase to produce oscillation through or around the path completed by this stray coupling. Interstage feedback between the coils in tuned circuits of the receiver is kept to a minimum by using small r-f coils, properly oriented in respect to each other, and shielded in metal inclosures. The tuning capacitors for the various stages are shielded from each other by metal plates to minimize electrostatic coupling. Critical leads in the plate and grid circuits carrying high signal voltages are kept as short as possible and are aften surrounded by shielding braid. Complete stages of the receiver may be placed in metal inclosures to prevent internal and external coupling.

b. In general, the problem of reducing interstage feed-back and external stray coupling resolves itself into careful electrical and physical design of components, correct mechanical layout, and sufficient shielding. Iron commonly is used for shielding audio-frequency circuits, and copper, aluminum, or brass is used for r-f circuits. All shields are connected to the chassis of the receiver, which serves usually as common ground for all connections. Since shields placed around tubes and coils change the resonant frequency of the tuned circuits with which they are associated, all tuning and alinement adjustments must be made with the shields in place.

110. Band Selection Methods

a. Single Control Tuning. Most trf receivers have two or three r-f stages ahead of the detector, all tuned to the same signal frequency. It is convenient to tune all r-f stages together by means of a multiple-section tuning capacitor. On such a ganged variable capacitor, the rotor plates of the individual capacitors are turned with a single tuning knob to the same relative positions in respect to the stationary (stator) plates, so that they all have the same capacitance. If the tuning coils and capacitors are identical, the resonant frequencies of the tuned circuits are the same.

b. Tracking. Because of mechanical difficulties in making the coils and capacitors of the same value, and becaus of stray circuit capacitances, it is found in practice that the circuits cannot all be tuned to exactly the same frequency for a particular dial setting. To compensate for these irregularities, small *trimmer capacitors* are connected in parallel with each tuned circuit. In receivers having only one frequency band, these trimmers usually are connected in parallel with the ganged capacitor, one for each section. In receivers with several bands, the trimmers are mounted on the individual coils. The trimmers are adjusted or alined at specific frequencies, so that all tuned circuits are in resonance at these frequencies and thus have maximum output. To insure that the tuned circuits remain in alinement at all dial settings, and not only at the particular alining frequencies, additional adjustments are necessary. In some receivers these are provided by means of slotted rotor end plates in the tuning capacitors. Any portion of these slotted plates can be bent closer to or farther away from the stator plates, thus permitting adjustment of the capacitance to obtain correct tuning throughout the frequency range. When all stages of the receiver tune to identical frequencies at all dial settings, they are said to be *tracking.*

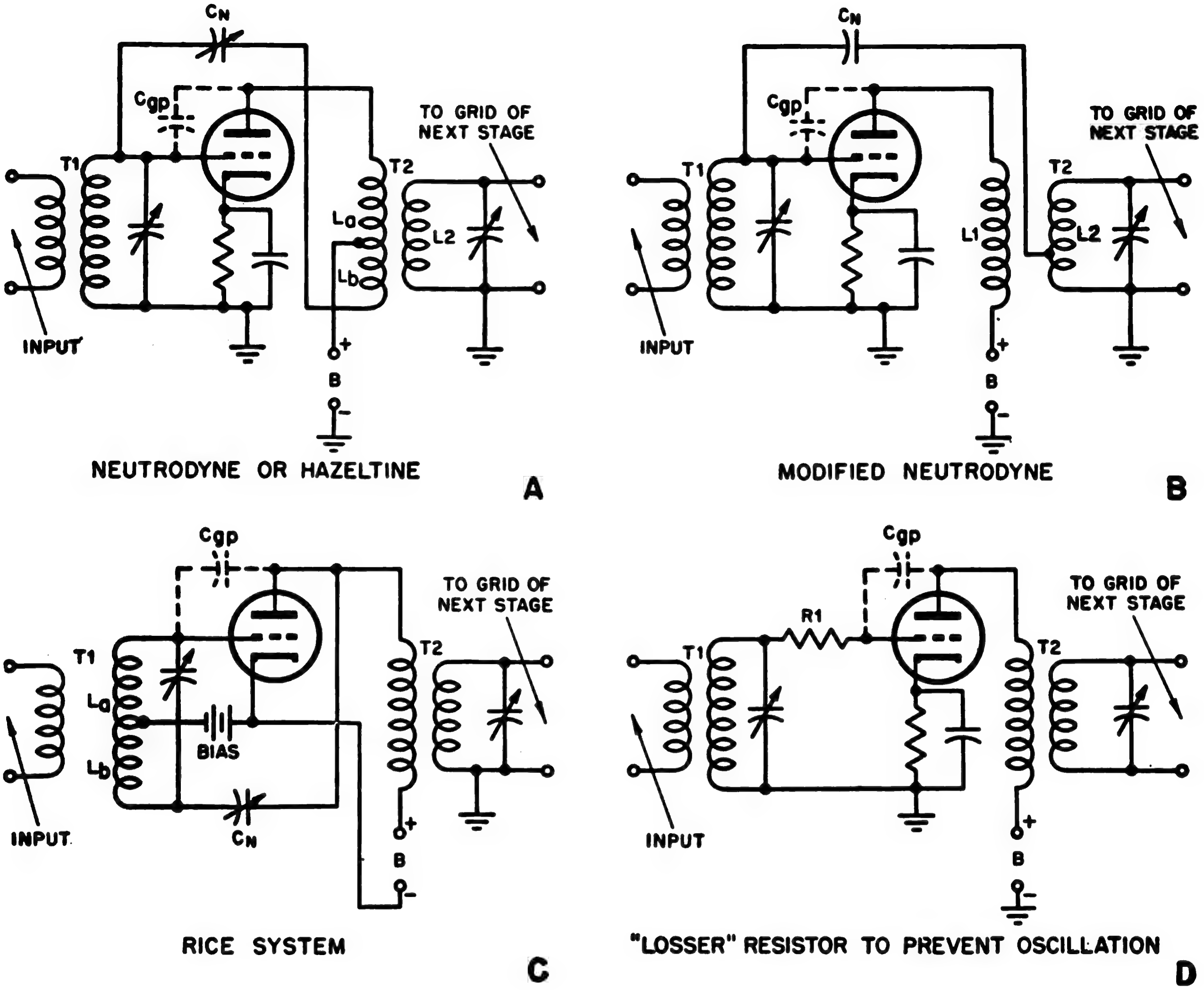
c. Band Switching. Each tuned circuit of the receiver is designed to cover a certain frequency range by means of its variable capacitor. Design difficulties limit the maximum frequency range that can be covered with a particular combination of coil and variable capacitor. If a greater frequency range is to be covered by the receiver, the tuned circuits must be modified. This usually is accomplished by substituting another coil in parallel with the same variable tuning capacitor. In some receivers, this substitution is accomplished by using a set of plug-in coils for each desired frequency band. In the great majority of receivers, however, the various coils for different frequency bands are mounted inside the receiver. The leads from each coil are brought out to a multicontact rotary switch, called a band switch. By turning the band switch, any desired frequency band may be selected. In both methods of band selection, the same tuning capacitors are used for all tuning ranges. Tracking or alinement must be carried out separately for each frequency band.

d. Band Spread. To permit separation of many stations which are crowded together on a small portion of the tuning dial, some receivers are provided with *band spread* arrangements. These spread out a small sector of the main tuning dial over the entire scale of a separate tuning dial. Band spread can be electrical or mechanical. In electrical band spread, a small tuning capacitor is connected in parallel with the main tuning capacitor of the tuned circuit. The tuning range of this band spread capacitor is a fraction of that of the main tuning capacitor. Thus, one complete revolution of the band spread capacitor modifies the total capacitance and therefore the resonant frequency of the tuned circuit by only a small amount. In mechanical band spread, a gear train is used between the band spread dial and the main tuning dial. One complete revolution of the band spread dial moves the main tuning dial and capacitor over a small fraction of its range, thus permitting precise tuning.

111. Triode R-F Amplifiers

a. Need for Neutralization. Despite their inherently low gain, triode tubes sometimes are used as r-f amplifiers in trf receivers. Because of their low gain, several r-f amplifier stages must be used to achieve the required sensitivity. It has been found in practice, however, that several triode amplifier stages in cascade tend to be unstable and produce oscillations. The reason for this is the cumulative effect of the feedback of energy from the plate circuit of each triode stage to its grid circuit through the relatively large grid-to-plate capacitance present in the triode tubes. It has been pointed out in the analysis of the tuned plate tuned grid oscillator (ch. 3) that the phase of this feedback depends on the plate-circuit impedance. If the plate circuit is resistive, the feedback energy is out of phase with the grid voltage (degenerative feedback exists), and consequently the gain of each stage is reduced. If the plate circuit is inductive, as is usual, the feedback energy is in phase with the applied grid voltage and regeneration takes place. This increases the gain of the stage by overcoming some of the losses in the grid circuit. If the regeneration is sufficient to overcome all losses in the grid circuit, the effective circuit resistance becomes zero, and oscillation takes place. In most cases, both degeneration and regeneration are undesirable and methods must be used to neutralize the feedback between the plate and grid circuits.

b. Neutralization Methods. For effective neutralization, the neutralizing circuit must provide to the grid circuit of each stage a signal voltage from the plate circuit which is equal in magnitude and opposite in phase to the feedback voltage, in order to cancel it completely (fig. 161).



NEUTRODYNE OR HAZELTINE

MODIFIED NEUTRODYNE

RICE SYSTEM

"LOSSER" RESISTOR TO PREVENT OSCILLATION

Figure 161. Typical neutralizing circuits.

(1) The *neutrodyne* or *Hazeltine* circuit, shown in A, is one of the most frequently used neutralizing circuits. Here, the primary coil of output transformer *T*2 is tapped so that the voltage at the lower end of L_b, which is connected to C_N, is 180° out of phase with the plate end of L_a. The energy fed back through neutralizing capacitor C_N is, therefore, out of phase with that fed back from the plate to the grid through C_{gp}. With the proper size of C_N, the neutralizing voltage is equal in magnitude and 180° out of phase with the feedback voltage, and cancels it completely. A modification of the neutrodyne circuit is illustrated in B. Here, the secondary coil, *L*2, of output transformer *T*2 is tapped, and a phase reversal takes place between primary coil *L*1 and secondary coil *L*2. The neutralizing voltage can be made equal in magnitude and 180° out of phase with

the voltage fed back through C_{gp} by adjusting the tap on $L2$.

(2) In the *Rice system* of neutralization, in C, the neutralizing capacitor, C_N, has a value such that the current flowing through it as a result of the plate circuit voltage equals that flowing through the grid-to-plate capacitance, C_{gp}. Since the the secondary of $T1$ is tapped, the currents through C_{gp} and C_N are in phase opposition and so neutralize each other.

(3) The circuit shown in D is designed to prevent oscillation by absorbing some of the energy fed back through C_{gp} in a *losser* resistor, $R1$, but it does not neutralize this energy. The ohmic value of $R1$ is a few hundred ohms and is connected in series with the control grid. Normally, the grid is biased negatively and no current flows through the losser resistor in the absence of oscillations; consequently, no loss in gain or selectivity takes place. If oscillation takes place, however, the grid is driven positive, and a current flows through the grid resistor. The presence of the resistor directly in series with the oscillating circuit causes electrical losses which tend to damp out the oscillations. The resistor, while not canceling out the feedback energy, tends to hold it below the level of regeneration required for oscillation. The grid resistor also tends to keep the gain over the frequency band more uniform, by absorbing more energy at the higher frequencies.

112. Advantages of Pentodes

The development of the tetrode tube, with the screen grid acting as a shield between the plate and control grid, has made neutralizing circuits in trf receivers unnecessary. It also raises the gain for each stage of the receiver, and thus permits the use of fewer amplifier stages for the same over-all sensitivity. Further improvement in the performance of r-f amplifiers is provided by modern high-gain pentodes. These provide greater gain per stage than any other type of r-f amplifier tube. The grid-to-plate capacitance of pentodes is reduced to a negligible value by the action of the screen and suppressor grids. R-f pentode amplifiers provide very high usable stage gains without regenerative feedback or oscillation. The majority of r-f pentodes in receivers are of the *variable-mu* or *remote cutoff* type, a feature which permits the use of avc (automatic volume control) with little distortion.

113. Detection

Detection is the process of extracting the transmitted intelligence from the modulated carrier wave. The detection or demodulation process consists of separating the audio-frequency variations from the radio-frequency carrier, and then discarding the carrier. In amplitude modulation, this is accomplished by first rectifying the modulated radio signal to obtain a pulsating direct current varying in magnitude in accordance with the original signal. These pulsations are then smoothed out with a filter, and the r-f carrier is discarded. The detector circuit combines these functions in a single stage. This action has been discussed in connection with the crystal receiver. Depending on their use and operation, detectors, in general, are characterized by such terms as *power*, *square-law*, and *linear*. A power detector is designed to rectify relatively large r-f signal voltages; a weak-signal detector is intended for a small r-f signal input. A linear detector develops a rectified output proportional to the amplitude of the r-f input voltage, whereas the output of a square-law detector is proportional to the square of the amplitude. Weak signal detectors are always of the square-law type, and power detectors usually are linear. Various types of detectors have been developed, each having certain advantages and limitations, depending on application. The most important and most frequently used types are the grid leak detector, the plate or bias detector, the infinite-impedance detector, and the diode detector.

a. Grid Leak Detector.

(1) In figure 162, which illustrates the circuit of the grid leak detector, A and B show a triode and pentode circuit, respectively. The action of both circuits is the same, but the pentode provides more amplification. In both, detection of the modulated signal takes place in the control grid-to-cathode portion of the tube, and amplification is achieved in the grid-to-plate portion. To illustrate the different possibilities, A shows an L-C filter and transformer coupling, and B uses an R-C filter and resist-

ance-capacitance coupling. Either method of filtering is feasible.

(2) In A, the triode grid and cathode are operated like a diode rectifier. The grid leak resistor, R_g, represents the load for the rectifier; grid capacitor C_g acts as a bypass for r-f. Assume that an r-f signal voltage, as in C, is present at the primary of *T*1 and is applied through C_g between the grid and cathode of tube *V*1. Initially, the tube has zero bias. When the signal input voltage drives it positive, the grid draws current. The grid current, which flows from the control grid through R_g, the secondary of *T*1, and back to the cathode, produces a negative voltage drop across the combination of R_g and C_g, as shown. This voltage drop is the bias for the tube. The relatively high capacitive value of grid capacitor C_g holds its negative charge during the negative half cycles of the signal voltage when no grid current flows. This action is cumulative and tends to bias the tube near cut-off. Consequently, plate current flows during the positive half cycles of the r-f signal and not during the negative half cycles.

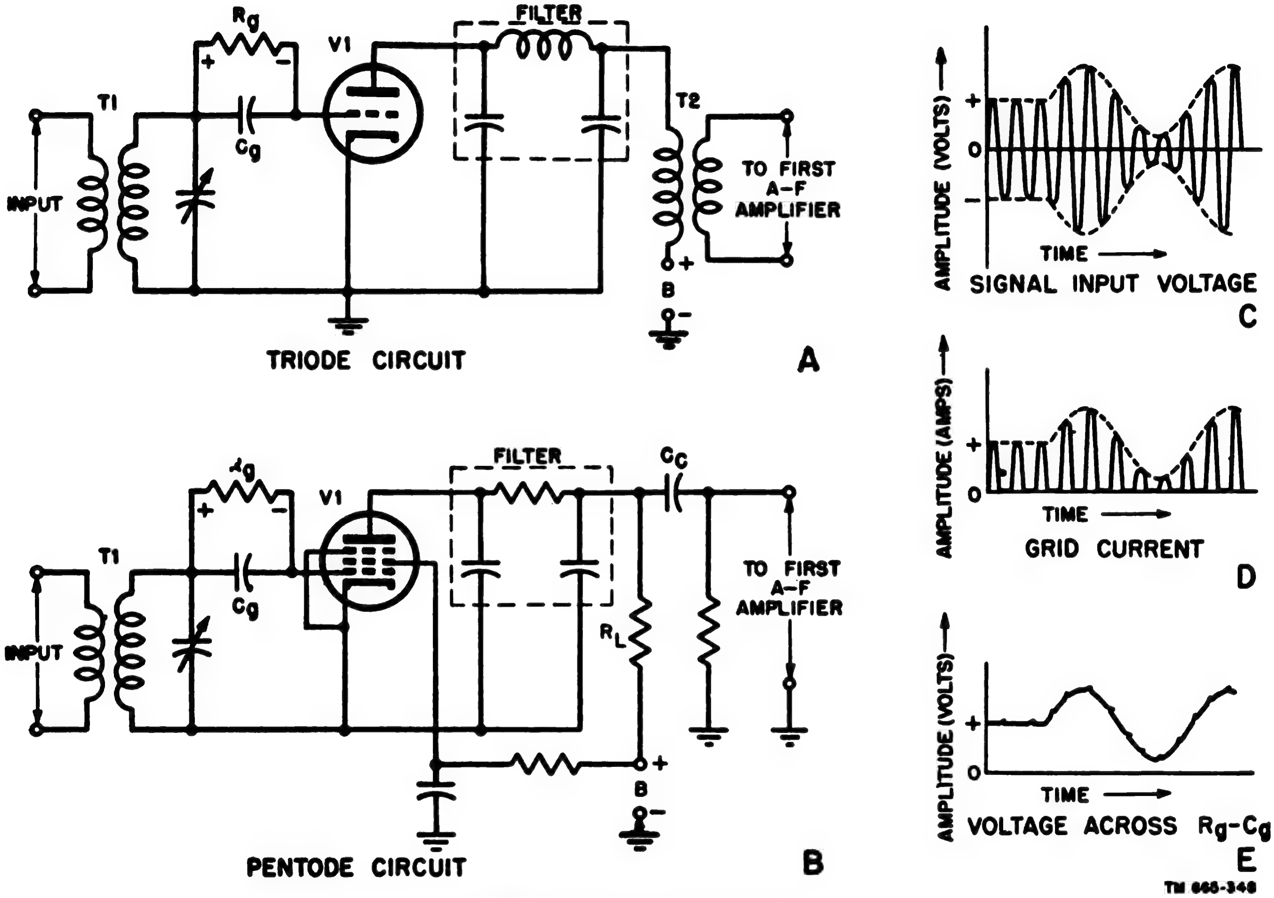


Figure 162. Grid leak detector.

(3) During the positive half cycles of the signal, grid current flows as in D. This pulsating d-c grid current produces a varying voltage across R_gC_g and consequently a varying negative bias. Because of the r-f filtering action of R_gC_g, however, this bias varies at the audio frequency of the modulation rather than at the frequency of the r-f carrier. The time constant (R_g times C_g) is chosen so that the charge on C_g leaks off very slowly through R_g and, therefore, cannot follow the rapid variations of the r-f carrier. However, it is capable of following the slower a-f variations of the modulation. Consequently, the voltage across C_g re-

produces only the *peaks* of the r-f carrier, as shown in E. Since the amplitude of these peaks varies as the a-f modulation, the voltage across C_g and, therefore, the bias also follow the modulation. This varying bias, or modulation, on the grid of the tube appears in amplified form in the plate circuit. An increase in bias decreases the plate current, and a decrease in bias increases the plate current. The r-f component of grid voltage also is amplified and appears at the plate. The a-f modulation component of the plate current, therefore, must be separated from the r-f component by a suitable *R-C* (resistance-capacitance) or *L-C* filter in the plate circuit. Freed of the r-f, the audio component then is coupled to the grid of the first a-f amplifier tube.

(4) As a weak signal or square law detector, the tube is operated at a low plate voltage and R_g is chosen between 1 and 5 megohms, with C_g having a value between 100 and 300 $\mu\mu$f. In this application, the grid leak detector is extremely sensitive for weak signals. Because of square law operation, however, the output is considerably distorted. With strong signals, the positive grid current overloads the tube, and additional distortion results. Also, since current is drawn from the tuned imput grid circuit for rectification, the selectivity of the tuned circuit usually is low.

(5) Less distortion of strong signals occurs if the circuit is operated as a grid leak power detector. For this application, the tube is operated at a higher plate voltage, R_g is reduced to approximately 100,000 to 500,000 ohms, and C_g is from 50 to 100 $\mu\mu$f.

b. Plate Detector.

(1) In a plate detector (fig. 163), rectification of the modulated r-f signal takes place in the plate circuit of the tube. A shows a typical circuit, with its principle of operation illustrated in B. The cathode bias resistor, R_k, is made sufficiently large to bias the tube near cut-off in the absence of a signal. This places the operating point in the lower bend of its i_p–e_g characteristic. The bypass capacitor, C_k, does not respond to r-f or a-f and therefore holds the bias at a constant value. The effect of applying an r-f signal to the grid of the tube under these conditions is as shown in B. The negative half cycles of the signal voltage drive the tube completely to plate current cut-off. These half cycles, therefore, are eliminated for the most part in the output of the tube. The positive half cycles of the signal drive the tube above the cut-off value, so that plate current flows throughout these half cycles. In effect, therefore, when the tube is operating near plate current cut-off, rectification of the r-f signal takes place. Because of the characteristics of the tube, amplification of the positive half cycles also occurs.

(2) The average value of the plate current pulses (shown by heavy solid lines) varies in accordance with a-f modulation of the signal. An r-f filter in the plate circuit removes the remaining r-f carrier component of the signal but permits free passage of the audio modulation, as represented by the average plate current. The a-f output signal then is either resistance- or transformer-coupled to the grid of the first a-f amplifier stage.

(3) For weak signals, the plate detector operates essentially in the curved square law portion of the i_p–e_g characteristic. As a result, considerable distortion of the output waveform occurs. For strong input signals, operation takes place over the more linear portion of the characteristic, and less distortion occurs in the output. The maximum signal-handling ability of the plate detector is limited, however, since the signal voltage must be below the value that would cause the grid to draw current. If grid current is drawn, the sensitivity and the selectivity of the detector are lowered. Another disadvantage of the plate detector is that it does not provide directly a voltage for avc. Pentodes usually are preferred as plate detectors because they provide a larger audio-output voltage triodes.

c. Infinite-Impedance Detector.

(1) The infinite-impedance detector circuit (fig. 164) is so-named because its grid in-

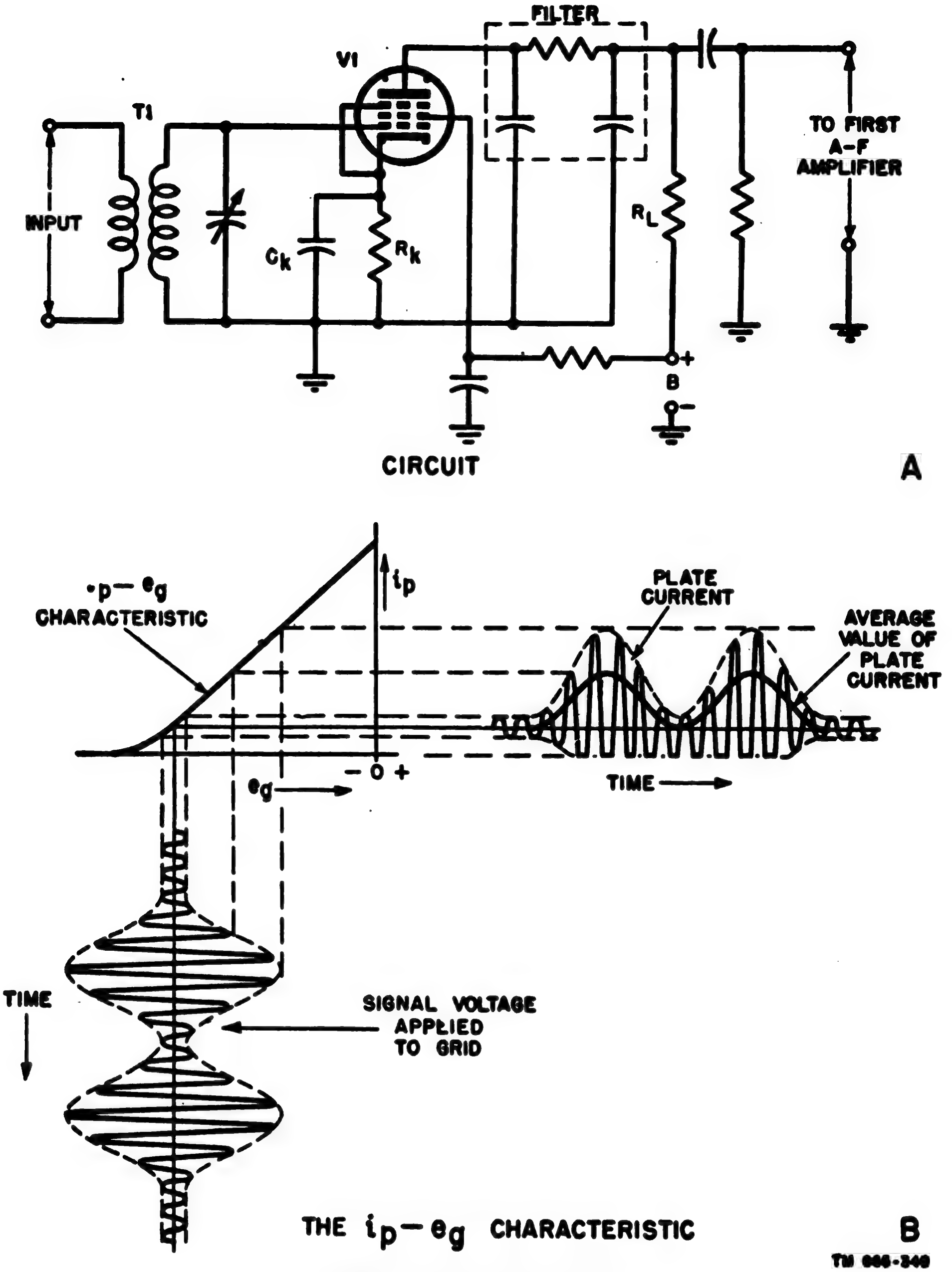


Figure 163. Plate detector.

put has theoretically infinite impedance, since the grid cannot be driven positive, regardless of signal strength, and consequently no grid current is ever drawn. As a result, the selectivity of the circuit is excellent. A further characteristic of the infinite-impedance detector is its good linearity (low distortion), and its ability to handle high signal input voltages.

(2) The circuit resembles that of the plate detector, except that the audio load resistor, *R*1, is connected between the cathode and ground and thus is common to both grid and plate circuits of the tube. Therefore, negative feedback from plate to grid circuit takes place at audio frequencies, which further improves linearity and reduces distortion at all signal levels. Since the output is taken from the cathode circuit, no amplification takes place, and the sensitivity of the circuit, therefore, is low. This is of little im-

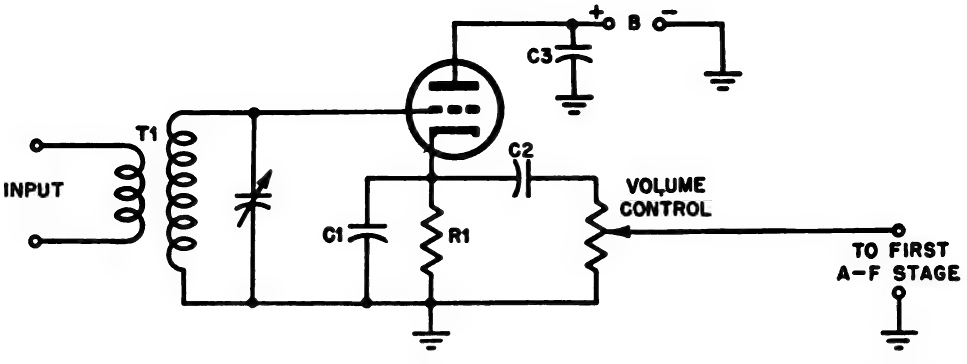


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Figure 164. Infinite-impedance detector.

portance in trf receivers using high gain r-f amplifiers ahead of the detector.

(3) The cathode load resistor, *R*1, serves two purposes: It acts as load for the rectified audio signal and it provides automatic bias near plate current cut-off of the tube. As in the plate detector, therefore, the negative half cycles of the signal are cut off, and rectification takes place. The rectified voltage appears across *R*1, and *C*1 filters out the r-f component. The capacitive value of *C*1 is chosen so that it bypasses the r-f fluctuations to ground but does not shunt out the audio-frequency signal appearing across *R*1. The plate is bypassed to ground for both audio and radio frequencies by *C*3. The audio voltage across *R*1 is coupled through *C*2 and the volume control to the grid of the first a-f amplifier stage.

(4) As in the case of the plate detector, the average plate current increases with the amplitude of the signal voltage. With increasing plate current, the voltage drop across *R*1 and consequently the bias also increase. The grid bias, therefore, adjusts itself automatically to the r-f input signal and the grid cannot be driven positive for any value of the signal. This is the reason for the high selectivity and excellent linearity of the circuit, even for very large signal voltages. The chief disadvantage of the infinite-impedance detector, in addition to low sensitivity, is its inability to supply a voltage for conventional automatic volume control circuits. A further disadvantage of the infinite-impedance detector is the fact that when the received signal is so weak that only a low value of signal is applied at the grid of the detector circuit, distortion will occur.

d. Diode Detector. Although having excellent linearity characteristics, diode detectors need a strong signal voltage for efficient operation and have low sensitivity. Their use is confined chiefly to the highly sensitive superheterodyne receivers, where large amplification takes place before demodulation. Diode detectors are discussed in the next chapter.

114. Volume Control

a. Volume or *gain controls* are provided in receivers to permit variation in the receiver sensitivity. This is necessary to compensate for differences in the strength of incoming signals. Volume control can be manual or automatic. The majority of trf receivers use manual volume control, since their gain is low. Automatic volume control is used universally in superheterodyne receivers, and is discussed later.

b. Two basic methods of manual volume control are in use. In one method, the volume of the audio signal is varied by changing the gain of one or more of the r-f amplifier tubes used in the receiver. This is accomplished by changing one of the controlling potentials applied to the tube, such as the grid bias, plate, or screen voltages. In the other method, the gain of the amplifiers themselves is not changed, but the signal is attenuated at some convenient point in the receiver by use of a variable shunt resistor or by tapping a portion of the signal voltage from a potentiometer-voltage-divider arrangement.

c. Figure 165 shows a few commonly used volume control systems. A shows a variable resistor, R, connected in parallel with the primary winding of the antenna transformer, $T1$. The lower the value of this resistor, the greater is the shunting effect and the lower the volume of the receiver. The disadvantage of this arrangement is that by shunting the primary of $T1$, the Q and, therefore, the selectivity of the first tuned circuit are lowered.

d. In B, the variable resistor, R, permits changing the bias and consequently the gain of the r-f amplifier stage. A remote cut-off (variable-mu) pentode is used for this application. Varying the grid bias of variable-mu tubes causes the amplification factor and the gain of the tube to change smoothly. The limiting bias resistor, R_c, prevents the bias of the r-f amplifier stage from being zero when R is adjusted to a minimum value. By increasing R, the bias is increased and the amplification is reduced. When using this method, the bias voltages of all r-f amplifier stages usually are controlled together. This is achieved by tying the cathodes of the amplifier tubes together.

e. In C, the gain of the r-f amplifier stage is controlled by varying the screen grid current and thus the screen grid voltage. This is accomplished by varying the variable screen resistor, R. The same effect can be produced by placing R in series with the plate.

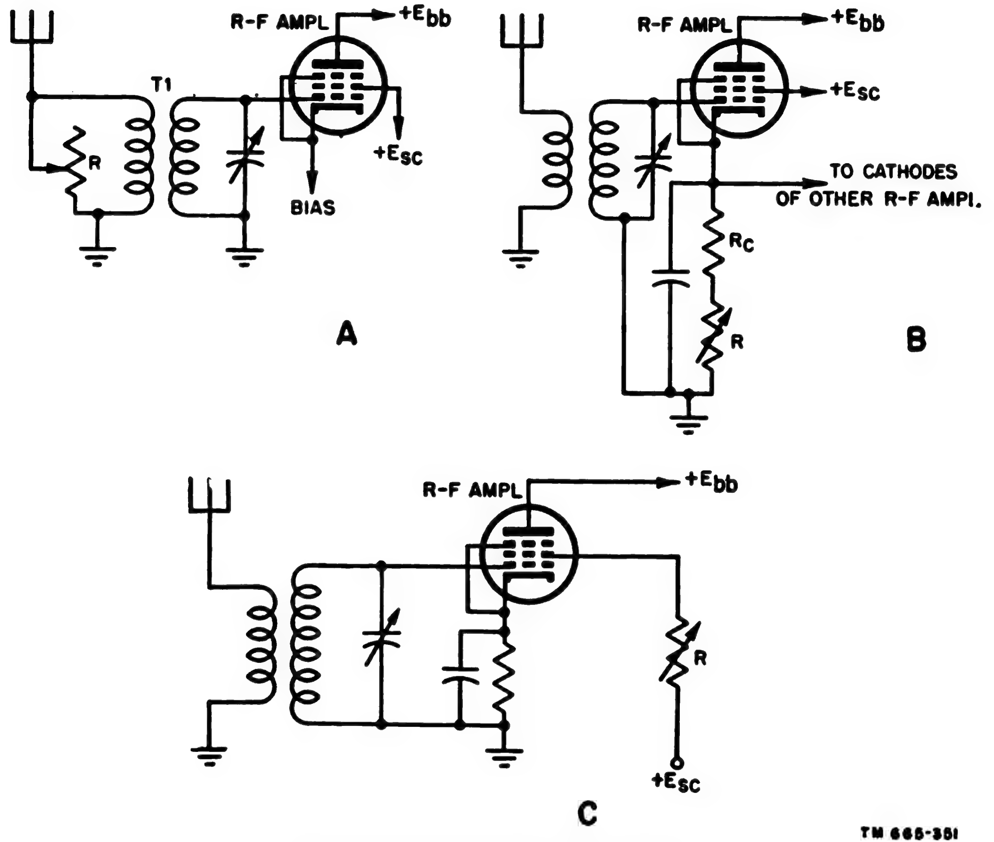

Figure 165. Methods of volume control.

115. Audio-Frequency Amplification

After a modulated signal has been detected, the audio-frequency variations usually must be amplified before they can be applied to drive a reproducer. In general, this involves one or more a-f voltage amplifiers and a power amplifier with sufficient output to drive the reproducer. These stages may be combined into a single a-f stage inserted between the detector and reproducer, particularly if a headset is used since it necessitates little audio power. Audio amplifiers and reproducers that are used in trf receivers are of the same type as those used in superheterodyne receivers. They are discussed in the next chapter.

116. Typical Trf Receiver

a. The basic elements of the typical five tube trf receiver (fig. 166) already have been discussed in

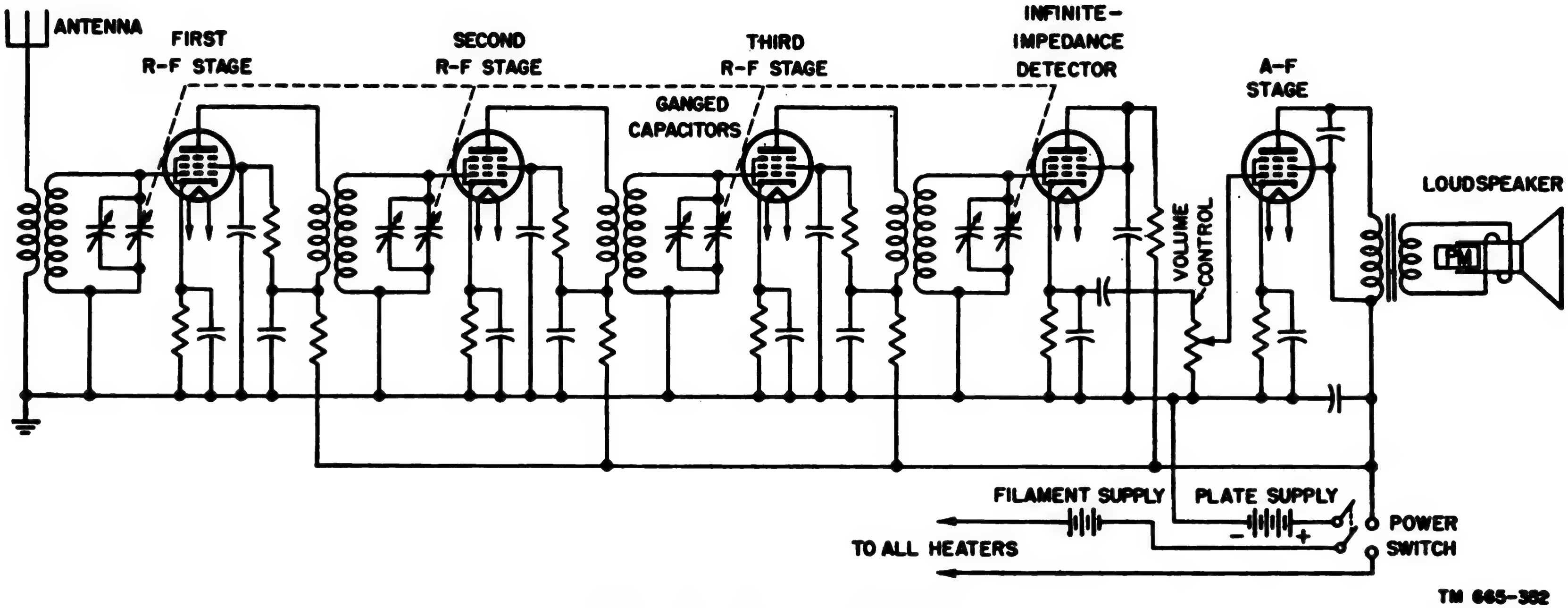

Figure 166. Battery type trf receiver.

detail, stage by stage. The antenna is coupled by an r-f transformer to the first r-f amplifier stage, which in turn feeds two more r-f amplifiers in cascade. Pentode tubes are used throughout the receiver for high gain. The last tuned r-f stage is coupled to an infinite-impedance detector. The input to the a-f stage is controlled by the volume control whose variable arm is connected to the control grid of the a-f stage. The output of the a-f stage is sufficient to drive the loudspeaker because a power pentode is used.

b. The heater and plate voltages for the vacuum tubes are provided by batteries connected into the circuit when the double-pole, single-throw power switch is closed. No separate bias supply is necessary, since all tubes operate with cathode self-bias. Three tuning capacitors are utilized in the inputs of trf stages, and one is connected in the input circuit of the detector stage. These four tuning capacitors are ganged to provide single control tuning, as indicated by the dotted lines in the diagram. A small trimmer capacitor is connected in parallel with each section of the ganged tuning capacitor to permit accurate alinement of the tuned circuits of the receiver. These small trimmers are used to compensate for inequalities in the circuit constants. The gain of the receiver is sufficient to take advantage of the highly linear, though relatively insensitive, infinite-impedance detector.

c. The resistors in the plate leads of the three r-f amplifiers are bypassed to ground by a capacitor. These *R-C* combinations in the plate circuits of amplifier stages are known as *decoupling* or *isolating* filters. Each resistor offers a high impedance to the r-f signal, and the capacitor bypasses it around the plate supply. Consequently, the function of the decoupling filter is to keep the r-f signal out of the plate supply. If these filters were not present, the r-f stages would be coupled together through the internal resistance of the common battery plate supply. The resulting regeneration would lead to instability and undesirable oscillation.

117. Limitation of Trf Receiver

A trf receiver with several stages of tuned r-f amplification gives good performance for a single low- or medium-frequency band, such as the broadcast band. Even in this application, the added expense of extensive shielding and decoupling filters between stages must be incurred to prevent instability and oscillation. This instability is present because the entire amplification takes place at the same signal frequency, and, therefore, the slightest coupling between output and input results in large feedback. Further, the trf receiver is not practical for use at high frequencies and as a multiband receiver, since its selectivity and amplification fall off rapidly at the higher frequencies.

118. Regenerative Detectors
(fig. 167)

a. Regeneration. Regeneration or *positive feedback*, is the process of feeding a portion of the output voltage of a vacuum tube circuit back into the input circuit so that it is in phase with the input voltage and reinforces it. The effect of regeneration is to lower the effective resistance of the tuned grid circuit, and raise its effective Q. This, in turn, substantially increases the voltage rise at resonance which is equivalent to added amplification, and also increases the selectivity of the stage. When regeneration is made large so that the effective resistance of the input circuit approaches zero, the resulting amplification is very great for extremely weak signals, but not quite as great for strong signals. If the feedback is increased to the point where the effective input resistance is equal to zero, sustained oscillation is produced. In the regenerative detector, feedback is carried to a point just below oscillation.

b. Circuit and Operation.

(1) The basic circuit of the regenerative detector, shown in A, combines the principles of both the tickler feedback oscillator and the grid leak detector. The fundamental difference between the regenerative detector and the tickler feedback oscillator is in the amount of feedback permitted. For radiotelephone reception, the feedback in the regenerative detector is adjusted so that it is just below the point of oscillation and gives a maximum of amplification. For c-w detection, the feedback is increased until oscillation actually takes place. The operation of the regenerative detector for c-w is discussed in chapter 9.

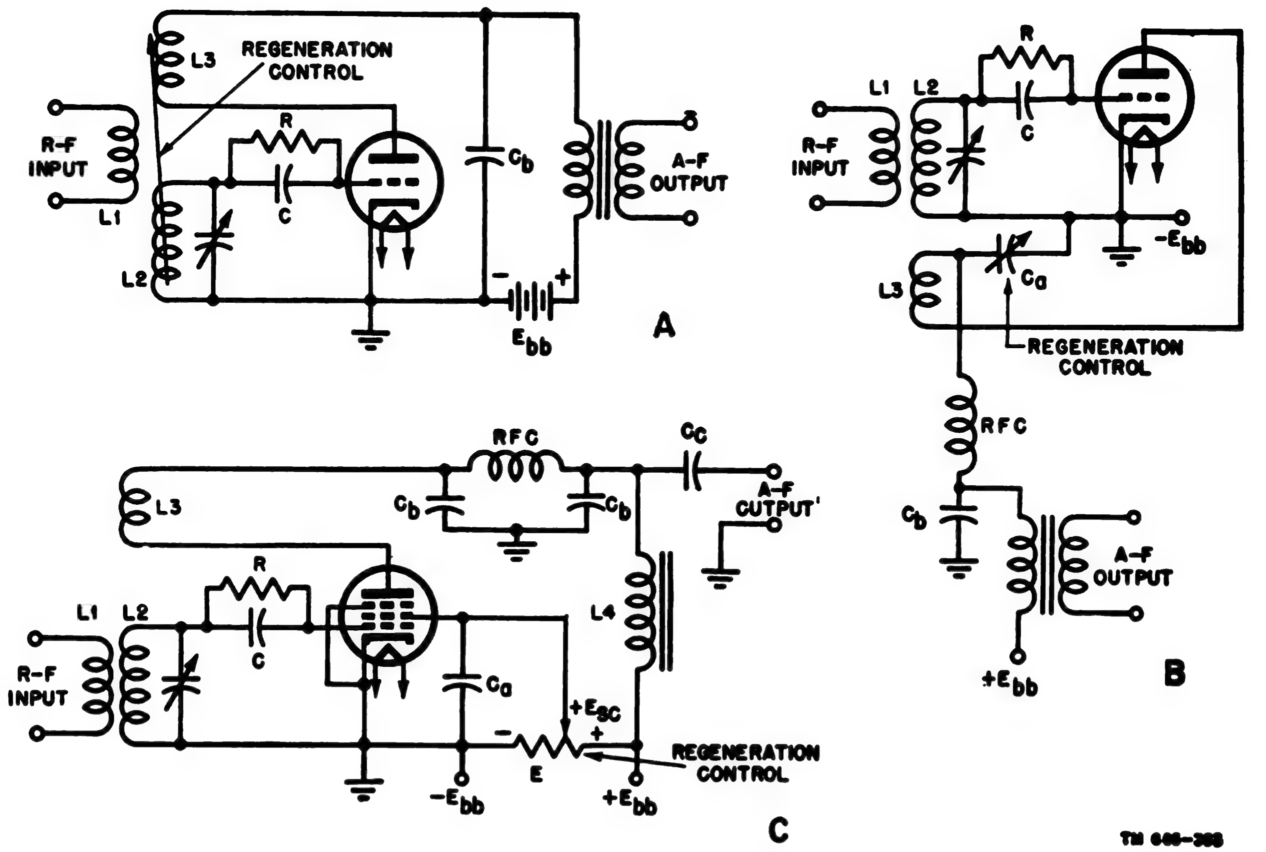

Figure 167. Regenerative detector circuits.

(2) In A, regeneration is applied to a grid leak detector circuit by connecting a *tickler* coil, *L3*, in series with the plate circuit and coupling it to the grid coil, *L2*. The output plate current from the tube flows through the adjustable tickler coil, producing magnetic flux which links the turns of the grid coil, *L2*, and induces a voltage in it. The tickler coil is so placed that the voltage induced in *L2* is nearly in phase with the r-f signal voltage and consequently reinforces it. The action is identical to that described in detail for the tickler feedback oscillator (ch. 3). Detection of the signal takes place in the grid circuit of the tube through the action of the grid leak resistance-capacitance combination, discussed in paragraph 113 above. The r-f signal from the antenna or a preceding r-f amplifier stage is applied to the input of the regenerative detector through the r-f transformer, *L1L2*. R-f energy in the output circuit is filtered out through capacitor C_b. In triode circuits, the a-f output is usually transformer-coupled to the grid of the first a-f amplifier, as shown in A.

c. Regeneration Control.

(1) In the early regenerative detectors, feedback was actually controlled by sliding or rotating the tickler coil, *L3*, and thus varying the mutual coupling between *L2* and *L3*. As the coupling is increased by bringing the coils closer together, more energy is transferred from the output to the input circuit. When the energy fed back is nearly equal to the energy lost in the grid input circuit, maximum sensitivity and selectivity result. However, for this condition the circuit is very unstable. A slight increase in signal strength or noise can cause the detector to break into self-oscillation. The degree of coupling, and so the regeneration, then must be reduced to stop the oscillation.

(2) Less cumbersome methods of controlling the feedback in a regenerative detector

are shown in B and C of figure 167. In the triode circuit, B, regeneration is controlled with variable bypass capacitor C_a (about 100 $\mu\mu$f) in the plate circuit. When the capacitance of C_a is made small, its reactance is high, and no regeneration takes place. As the capacitance of C_a is increased, its reactance becomes smaller, and regeneration occurs. The regeneration increases up to a critical value where the circuit breaks into oscillation. The regeneration control is advanced to a point just below this critical value. As in A, input and output are transformer-coupled; this is the most efficient coupling method for triode tubes. The r-f signal is tuned in with the resonant *L-C* tank and is detected by the *R-C* grid leak combination in the grid circuit. The r-f component of the plate current is filtered out by the r-f choke and bypass capacitor C_b. This combination acts as a low pass filter.

(3) Control of regeneration also can be accomplished by adjustment of the screen grid potential in a pentode, as shown in C. A variable potentiometer voltage divider permits changing the screen grid voltage of the tube from a low value to the maximum permissible, determined by the tube operating conditions. As the screen potential is increased by advancing the regeneration control, the amplification of the tube and of the positive feedback also increases, until a critical value is reached at which oscillation occurs. The portion of the regeneration control between the rotating contact and ground is bypassed by the screen grid bypass capacitor, C_a (.5 μf or more). This capacitor also helps to filter out the scratching noise caused by rotation of the arm. R-f in the plate circuit is filtered out by the low pass filter consisting of the r-f choke and bypass capacitors, C_b. For pentodes, impedance coupling of the a-f output to the next stage can be used to advantage. *L4* and C_C accomplish this purpose. The remainder of the circuit is similar to A and B. In place of the tickler feedback coil, *L3*, in *C*, an oscillating circuit of the Hartley type often is used.

(4) Ideally, the regeneration controls illustrated would permit the detector to go into and out of oscillation smoothly and would be independent of the resonant frequency and loading of the input circuit. In practice, these conditions are not present. Loading of the input circuit is unavoidable, particularly when the detector circuit is coupled directly to the antenna. The effect of changes in loading is to vary the effective *Q* and therefore the amplification of the resonant input circuit. This, in turn, affects the amount of regeneration. In addition, the characteristics of the tuned circuit (*Q* and selectivity) usually vary with the signal frequency, which again influences the amount of regeneration. The converse effect also occurs. Regeneration not only lowers the effective input resistance of the tuned circuit, but also changes its effective reactance slightly. This, in turn, detunes the tank circuit to some degree. All these effects tend to make the adjustment of the regeneration control very critical and unstable.

d. Method of Tuning. In addition to the regeneration control, regenerative detectors are provided with a tuning control, consisting of a variable capacitor in the grid tank circuit. Regenerative receivers usually are tuned by advancing the regeneration control beyond the point of oscillation and *zero beating* the incoming signal. When the frequency of the incoming signal is close to the frequency of oscillation produced by the regenerative detector, the difference between these two frequencies produces an audible tone, called a *beat frequency*. (The process of producing beat frequencies is known as *heterodyning* (ch. 9).) The tank circuit can be tuned exactly to the incoming signal frequency by adjusting the tuning capacitor slowly in a given direction until the audible tone is reduced in frequency and finally disappears. The frequency of local oscillation then is equal to the frequency of the incoming signal, and the tank circuit is tuned exactly to resonance. After the signal has been tuned in, regeneration is reduced to a point just below oscillation, in the case of radiotelephone reception. The selectivity and the sensitivity of the circuit are then at a maximum.

This method of tuning a regenerative receiver may cause radiation of the local oscillations and so produce strong interference in nearby receivers tuned to the same frequency. For c-w reception, continuous local oscillations are desired, and regeneration is kept high.

e. Limitations. Although they represent an inexpensive means of obtaining high sensitivity and selectivity, regenerative detectors have several disadvantages. The tuning is so sharp that the higher side-band frequencies contained in the signal tend to be eliminated, and consequently, the fidelity of reception is poor. More important is the fact that optimum regeneration depends on the frequency of the signal, and consequently the regeneration control must be readjusted for every new signal to be tuned in. It has been pointed out that the required adjustments are rather critical, and so time consuming. Moreover, because of the inherent instability of the circuit, these adjustments tend to be impermanent, and may have to be repeated from time to time. The circuit easily can break into oscillation and produce annoying squeals by beating with incoming signals. While oscillating, the detector is likely to interfere with nearby receivers. The latter effect can be reduced somewhat by using one or more r-f stages ahead of the regenerative detector, to suppress radiation. Because of these disadvantages, regenerative detectors are now used to only a small extent.

119. Superregenerative Detectors

A regenerative detector which is alternately thrown in and out of oscillation at a low radio-frequency rate is known as a *superregenerative detector.* By varying the plate voltage of such a detector at a low radio frequency, oscillations build up during the half cycles when the plate is positive, only to be suppressed or *quenched* when the plate is negative. By this principle of super-regeneration, the detector can be maintained continuously just at the point of oscillation where the operating conditions are most favorable. In this way, more regeneration can be obtained than in the conventional regenerative detector, and, consequently, the circuit becomes extremely sensitive without sacrificing stability.

a. Basic Action.

(1) To understand the principle underlying superregeneration, the action of an ordinary L-C tank circuit is reviewed. Damped oscillations take place when th capacitor of a tank circuit is discharge suddenly. The oscillations are damped out because of the resistive losses in the tank circuit. To make the oscillations continuous, or undamped, these losses must be overcome completely. In the vacuum-tube oscillator, this is achieved by feeding back a sufficient portion of the energy in the output in phase with the input tank circuit in order to overcome its losses. The feedback energy can be looked upon as introducing a negative resistance into the tank circuit which neutralizes its positive resistance. If the positive resistance of the tank is canceled out completely by the negative resistance, the effective resistance of the tank equals zero, and the circuit breaks into continuous self-oscillation. If the effective resistance of a tuned grid circuit could be varied periodically from positive to negative values, the circuit would build up oscillations during the intervals when the effective input resistance is negative, and the oscillations would be damped out or quenched during the positive resistanc intervals. This periodic variation of the effective tuned circuit resistance and the resulting alternations between oscillation and quenching are accomplished in the superregenerative detector.

(2) The basic circuit of a superregenerative detector (A of fig. 168) consists of a regenerative detector supplied with a plate voltage that is a low radio frequency (from about 20 to 100 kc). This *quenching* frequency can be supplied by a separate quenching oscillator or by the detector circuit itself, in which case it is known as a *self-quenching* circuit. If the tickler coil is adjusted to provide sufficient feedback, oscillations at the signal frequency build up during the half cycles when the plate voltage is positive and die out during the negative half cycles of the plate voltage.

(3) During the time when the plate voltage is positive, the feedback energy rapidly reaches a value sufficient to overcome the losses in the tuned grid circuit. There-

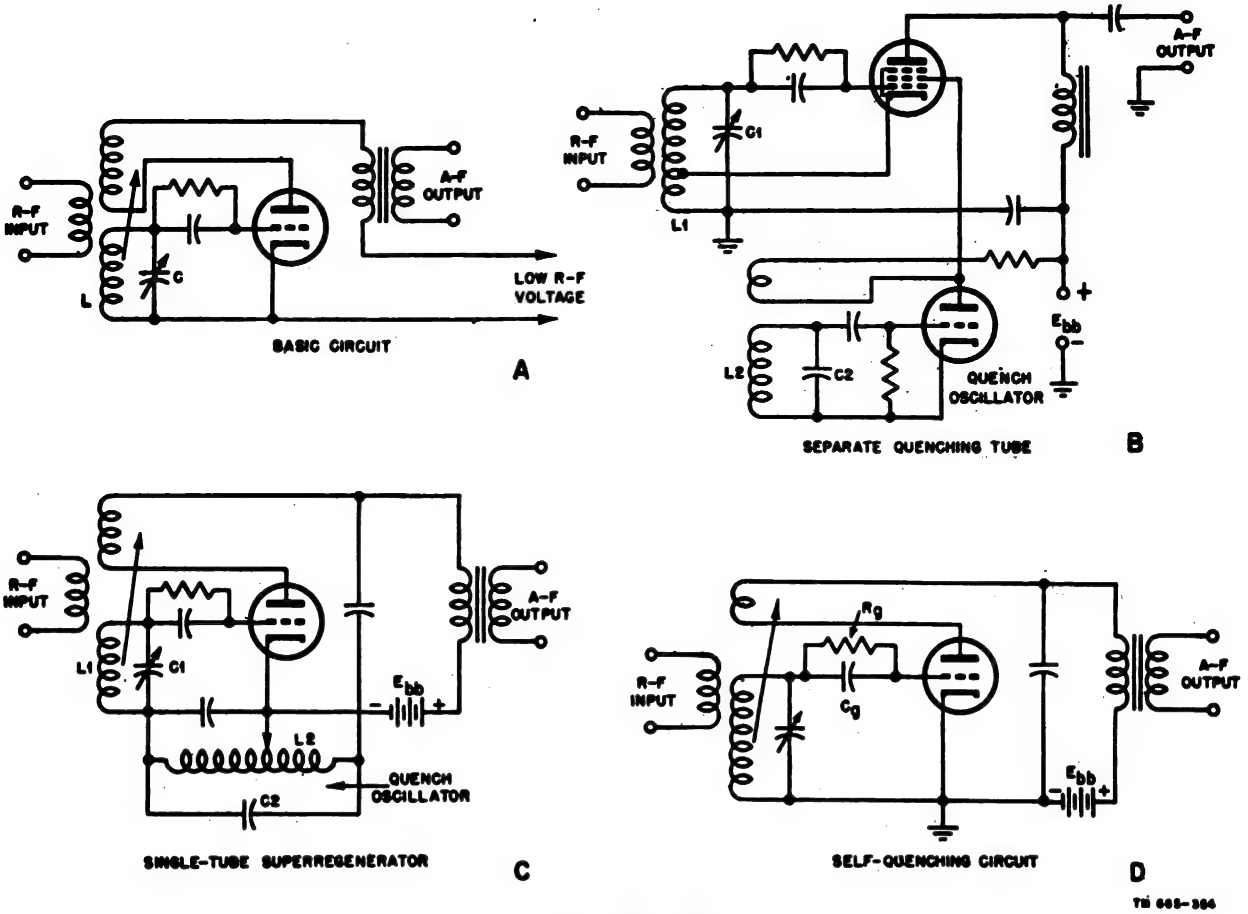

Figure 168. Superregenerative detectors.

fore, the effective resistance of the tuned input circuit becomes negative and oscillations build up. As the plate voltage decreases and finally becomes negative, however, the feedback energy also progressively decreases until it is no longer sufficient to overcome the losses of the resonant circuit. Consequently, its effective resistance becomes *positive* and the oscillations decrease in amplitude and finally cease; whenever the r-f plate voltage is positive, the effective resistance of the tuned input circuit is negative and oscillations start; whenever the plate voltage is negative, the effective tuned circuit resistance is positive and the oscillations are quenched. For proper operation, the oscillations must die out completely before they start to build up again.

(4) When no signal is present at the input, the initial impulse that starts the building up of oscillations is some form of random noise voltage, thermal agitation, shot effect, or other disturbance. Since the amplitude of these initiating pulses depends on chance factors, the amplitude and the length of the oscillating intervals themselves also differ in a random manner. As a result, the rectified output of the detector contains a characteristic hiss in the absence of a signal. Upon application of a signal with an amplitude exceeding the random noise voltages, the signal itself initiates the oscillations and thus suppresses the hiss. The building up of oscillations also occurs faster than in the absence of the signal. The time required to reach full amplitude of oscillation depends on the amplitude of the initiating signal pulse, and so the oscillating cycles themselves vary with the amplitude modulation of the signal. Rectification of the signal oscillations is

obtained with the grid-leak resistance capacitance combination in the same manner as in the conventional grid-leak detector. Filtering must be provided also.

b. Quench Frequencies.

(1) A careful compromise is necessary between the constants of a particular superregenerative detector and the frequency (as well as amplitude) of the quenching oscillations. Quench frequencies varying between approximately 20 kc and 100 kc have been used. Since the quench frequency must not be audible, 20 kc usually is considered the lower limit. If the frequency is lower, an a-f filter must be used to remove it from the audio output. The quench frequency must not be so low, however, as to cause the output and the sensitivity of the detector to become low.

(2) With increasing quench frequency, the sensitivity of the detector also increases, until an optimum value is reached. At this frequency, the oscillations just have time to approach full amplitude before they are quenched again. If the quenching frequency is raised above this value, the oscillations are suppressed before they have time to build up to full amplitude, and a considerable loss in sensitivity results. Further, if the quench frequency is too high, its harmonics may beat with the received signal and so cause interference. The ratio between signal and quench frequency usually is maintained at 100 to 1, or better. Quench frequencies between 70 and 100 kc are preferred for high-frequency operation, an application in which the superregenerative detector has the ability to provide radio frequency amplification and over-all sensitivity which is difficult to achieve with more conventional amplifier circuitry.

c. Separate Quenching Tube. A superregenerative detector with a separate quench oscillator is shown in B of figure 168. For the sake of variety, a Hartley oscillator circuit has been illustrated in the regenerative detector portion, although a tickler feedback circuit could be used equally well. The detector is tuned to the incoming signal by the input tank circuit, $L1C1$. The quenching oscillator consists of a conventional tickler feedback oscillator. Its frequency is determined by the tank circuit, $L2C2$. The output of the oscillator is coupled to the screen grid of the detector tube. The action of the circuit is identical with that discussed above.

d. Single-Tube Circuit.

(1) C is an illustration of a superregenerative detector utilizing a single tube with a separate low-frequency oscillating circuit. Regeneration in the detector portion is obtained with a tickler feedback circuit, and the quenching frequency is produced by a Hartley oscillator connected between the plate and grid circuits of the tube. As before, the signal is tuned in with the $L1C1$ tank circuit, and the quenching frequency is fixed by $L2C2$. In this form of self-quenching circuit, the tube performs a dual function: It detects and amplifies the incoming signal, and it produces sustained oscillations in the quench oscillator circuit.

(2) The superregenerative action is as follows: Since the quench oscillator is connected to the grid circuit, the oscillator output serves to shift the grid bias back and forth. This has the same qualitative effect on the amplification, feedback, and effective tuned circuit resistance as varying the plate voltage. At the positive half cycles of the quench frequency, the grid is driven positive, the plate current and amplification increase cumulatively (because of the increased feedback), and oscillations start. At the negative half cycles of the quenching frequency, the grid is driven highly negative, with a consequent reduction in amplification and feedback, and therefore the oscillations die out. This cycle is repeated over and over again at the quenching frequency.

e. Self-Quenching Circuit. A superregenerative detector circuit without a separate quenching circuit is shown in D. Outwardly this circuit is identical with the regenerative detector circuit illustrated in A. The basic difference lies in the values used for the grid leak resistor and capacitor, R_g and C_g. By making the values of these components relatively large and with sufficient regeneration, the circuit produces intermittent oscillations, which are self-quenching. Although the process of intermittent operation of a tickler feedback oscillator has been discussed in detail in chapter 3, it is reviewed here briefly.

(1) In the ordinary oscillator, the grid leak bias is self-adjusting and keeps the amplitude of oscillations at an equilibrium value. If the amplitude of oscillation should momentarily decrease because of some chance irregularity, the grid leak current and the bias also decrease. As a result, the amplification of the tube increases and compensates for the decrease in the amplitude of oscillation. If the amplitude of oscillation should increase, the reverse process takes place.

(2) If the time constant of the grid-leak combination, R_g times C_g, is large, the bias voltage can adjust itself only very slowly to sudden changes in the amplitude of oscillation. With the bias relatively constant, any slight irregularity tends to reduce the amplitude of oscillations and then causes them to die out by a cumulative process. After the oscillations have stopped, the grid capacitor, C_g, gradually discharges through the grid leak, R_g, thus reducing the bias until the tube amplifies again, and oscillations start to build up. The frequency of the interruptions in operation (quenching frequency) can be controlled by varying either the regeneration or the grid-leak resistance.

f. Advantages and Limitations. A superregenerative detector is characterized by extreme sensitivity for weak signals. It is less sensitive for strong signals, since the large amount of regeneration limits the maximum output produced by strong signals to slightly more than that for weak signals. Because of this, the circuit is less susceptible to strong intermittent noise voltages, such as ignition noises, than are most other receivers. The detector also has a high degree of stability and operates well on high-frequency signals. On the other hand, superregenerative detectors have several disadvantages. There is always a characteristic hiss in the absence of a signal. Because of the quenching action, the selectivity is poor. Like any other oscillator, the circuit radiates strongly. This generally necessitates a tuned r-f stage ahead of the detector, to keep down interference caused by radiation.

120. Summary

a. A receiver intercepts a tiny portion of the radio energy radiated by a transmitter and recovers the intelligence contained in it.

b. A receiver performs six essential functions:

(1) The antenna intercepts the signal.
(2) Tuned circuits select the desired r-f signal.
(3) Trf amplifiers strengthen the r-f signal.
(4) The detector stage demodulates the signal.
(5) After detection, a-f amplifiers increase the strength of the audio signal.
(6) A reproducer translates the audio variation into the corresponding sound waves, and thus reproduces the original intelligence.

c. A crystal receiver consists of an antenna, a tuned input circuit, a crystal detector, and a reproducer.

d. A trf receiver has one or more stages of r-f amplification, a detector, an audio amplifier, and a reproducer.

e. All the tuned circuits of a trf receiver operate at the frequency of the incoming signal.

f. A trf amplifier has a tuned input circuit for signal selection and a vacuum tube for signal amplification; it is coupled to the next stage, usually through an r-f transformer.

g. Selectivity is the ability of a receiver to differentiate between the desired signal frequency and all unwanted signal frequencies.

h. Fidelity is the characteristic of a receiver which permits it to amplify a band of frequencies containing the modulation without discrimination or distortion.

i. The sensitivity of a receiver is expressed in microvolts for a standard output.

j. Signal-to-noise ratio limits the usable sensitivity of a receiver; it is the ratio of signal strength to noise present at the input of a receiver.

k. The trf amplifier helps to prevent radiation of radio-wave energy produced in the regenerative detector circuit of the receiver.

l. The antenna coupling system can be direct, capacitive, untuned transformer coupling or tuned transformer coupling; the latter is more widely used.

m. Interstage coupling between r-f stages can be transformer coupling, impedance coupling, or resistance-capacitance coupling; tuned-transformer coupling is most common, although tuned-impedance coupling can be used in conjunction with permeability tuning.

n. Shielding is necessary in r-f stages to prevent undesirable feedback and spurious oscillation resulting from stray capacitive and inductive coupling; correct mechanical design and layout also are required.

o. Single-control tuning is made possible in trf receivers having several tuned stages by ganging the variable capacitors on a common shaft; consequently, all tuned circuits are adjusted to the same frequency.

p. Trimmer capacitors are connected in parallel with tuned circuits to compensate for small irregularities and permit tracking of all tuned circuits throughout the frequency range.

q. Triode r-f amplifiers must be neutralized to prevent feedback of energy from the output circuit to the input circuit of the tube through the grid-to-plate capacitance. In the absence of neutralization, regeneration and possible oscillation can occur.

r. Pentodes in the r-f stages of a receiver have more gain than triodes and do not need to be neutralized.

s. Detection or demodulation is performed by rectifying the modulated carrier and filtering out the r-f. The result is an audio frequency which corresponds to the modulation at the transmitter.

t. A weak signal or square-law detector is intended for small r-f signal input, whereas a power detector is designed to rectify relatively large r-f signal voltages.

u. The signal handling capacity of a detector is its ability to rectify relatively large signal inputs with a minimum of distortion.

v. A linear detector develops a rectified output proportional to the amplitude of the r-f input voltage, whereas a square-law detector has an output proportional to the square of the amplitude of the r-f input.

w. A trf receiver gives good performance for a single low- or medium-frequency band, but is not practical for use at high frequencies, since its selectivity and amplification fall off rapidly with frequency. It is also inherently unstable.

x. A regenerative detector combines the principles of a tickler feedback oscillator and those of a grid-leak detector; by the introduction of a controlled amount of regeneration in the circuit, the regenerative detector becomes extremely sensitive for weak signals.

y. A superregenerative detector is a regenerative detector which is alternately thrown into and out of oscillation at a low radio frequency known as the quenching frequency.

121. Review Questions

a. Describe the essential functions of a receiver.

b. How is the signal detected in a crystal receiver?

c. Describe the essential parts of a trf receiver.

d. Define *selectivity*, *fidelity*, *sensitivity*, *signal-to-noise ratio*.

e. List various types of noise and their causes.

f. How does a trf stage suppress radiation?

g. Differentiate between various types of antennas and interstage coupling.

h. Why is shielding necessary in trf receivers?

i. How are single-control tuning and band selection accomplished in trf receivers?

j. Define *tracking* and *alinement*.

k. Why is neutralization necessary?

l. What are the advantages of pentodes in trf receivers as compared to triodes?

m. What happens in the process of detection?

n. Define the following terms: linearity, signal-handling ability, weak-signal detection, power detection, square-law detection.

o. Describe the operation of a grid-leak detector, a plate detector, and an infinite-impedance detector.

p. Describe and compare various methods of obtaining volume control.

q. What is the function of decoupling filters in trf receivers?

r. List the relative advantages and disadvantages of a trf receiver.

s. Describe the operation of a regenerative detector.

t. How does a superregenerative detector differ from a regenerative detector?

CHAPTER 8

SUPERHETERODYNE RECEIVERS

122. Superheterodyne Principles

a. In the trf receivers studied in the last chapter, r-f amplification takes place at the frequency of the incoming r-f signal, and all tuned circuits are adjusted to this frequency. The superheterodyne receiver differs essentially from the trf receiver in that it *changes* the frequency of the received signal to a *fixed* value at which the tuned amplifying circuits can operate with maximum stability, selectivity, and sensitivity. The conversion of the received signal frequency into a lower (i-f) frequency in the superheterodyne receiver is based on the *heterodyne*, or beam, *effect*.

b. It has been pointed out (par. 117) that the trf receiver suffers from several disadvantages inherent in its operation. Since all its r-f stages function at the same frequency, stray coupling between output and input circuits may provide sufficient feedback to cause instability or oscillation. Furthermore, it is difficult to achieve uniform amplification of the r-f stages over the entire frequency range of the receiver. At the higher frequencies, the gain of each stage tends to fall off, and therefore the sensitivity of the receiver is reduced. Finally, the most serious drawback of the trf receiver is that the selectivity of the tuned circuits cannot be kept uniform over the frequency range. At the high-frequency end of the tuning range, the selectivity of the trf receiver decreases markedly. This lack of selectivity can become serious at the higher frequencies generally used in Signal Corps communication systems.

c. The inherent difficulties of the trf receiver are overcome to a large degree in the superheterodyne circuit by conversion of the signal frequency to a lower *intermediate frequency*. This frequency usually has a value below the carrier frequency of the incoming signal. Regardless of the value of the received signal frequency, the signal with its audio modulation is always converted to this fixed intermediate frequency. Then it can be amplified to the desired degree in a fixed-frequency i-f amplifier. This amplifier can be designed to have much higher and more uniform amplification and selectivity per stage over the tuning range of the receiver than is possible with a variable-frequency amplifier.

d. At the lower frequency of the i-f amplifier, it is possible to obtain more amplification than in the trf amplifier without the trf difficulties of feedback and oscillation. Furthermore, the selectivity of an i-f amplifier is considerably greater than that of an r-f amplifier operating at higher signal frequencies. Summing up, the superheterodyne circuit is superior to the trf receiver, because it is more selective, and has higher gain per stage and uniform selectivity and sensitivity. In addition to these advantages, it has fewer variable-tuned circuits and is more easily adapted to multiband reception. For these reasons, superheterodynes have replaced trf receivers in practically all applications.

123. Beat Frequencies

The production of beat frequencies can best be understood by considering first a similar effect with sound waves.

a. When two notes close in pitch (frequency) are sounded at the same time, a throbbing or pulsating sound is heard. These pulsations, or beats, occur at a frequency equal to the frequency *difference* between the two notes and are caused by interference between their sound waves. This effect often is observed when two notes in the lower registers of a pipe organ are sounded together, or when two tuning forks which differ slightly in pitch are struck.

b. The production of a beat note is illustrated in figure 169. Assume that two tuning forks are struck at the same time, one with a pitch of 90 cps,

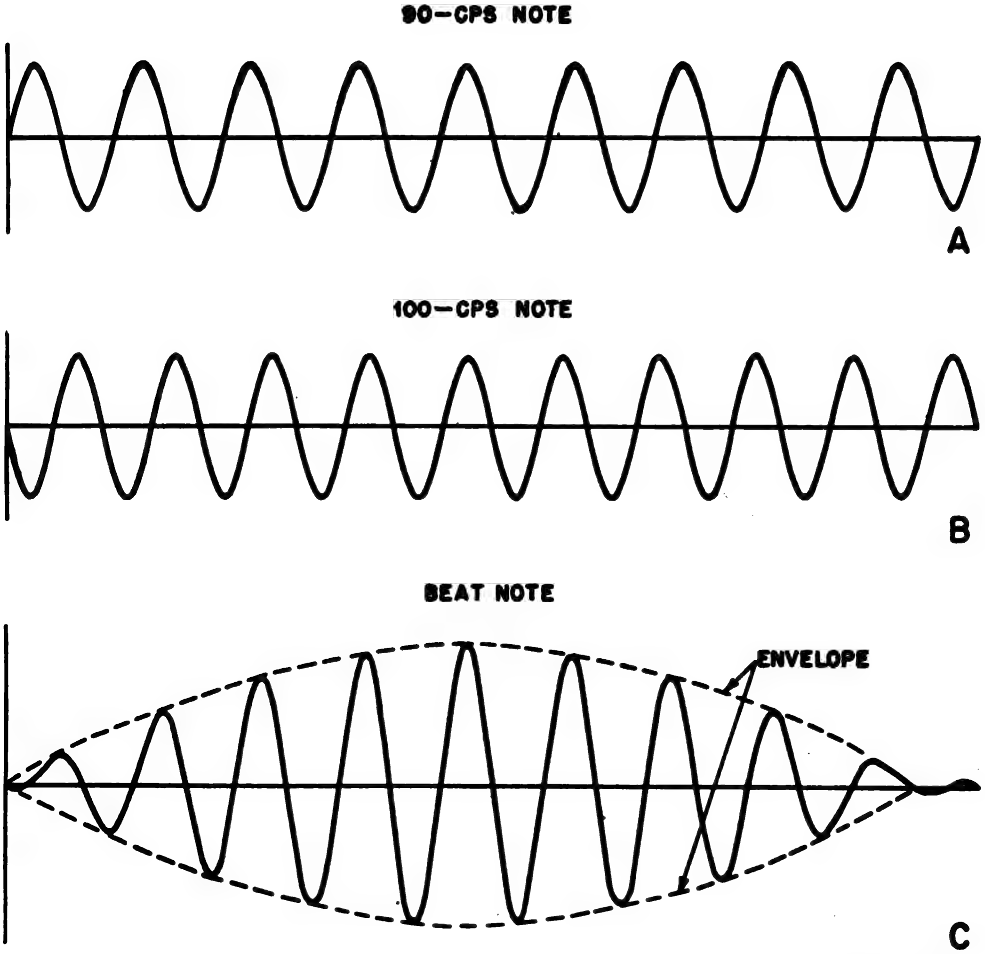

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Figure 169. Production of beat frequency.

as in A, the other, in B, with a pitch of 100 cps. The two tones are represented graphically by sine waves; 9 cycles of the 90-cps tuning fork and 10 cycles of the 100-cps fork are given. It is found that the two sound waves interact with each other. Sometimes they are vibrating together (in phase); at other times they are completely opposed to each other (out of phase). Whenever the two waves are in phase with each other, their amplitudes add, and they reinforce each other. Whenever the waves are in opposition, their amplitudes subtract from each other, and the sound waves interfere with each other.

c. In between these two extremes the waves reinforce or interfere with each other in varying degrees. This is clearly brought out in part C. Here the amplitudes of the two tones have been added algebraically to obtain the resultant waveform. Initially, the two notes are in opposition, and their resultant amplitude is zero. After approximately 5 cycles have passed, the forks vibrate in phase, and the resultant amplitude is the addition of the amplitudes of both waves. After approximately 10 cycles, the two notes are again out of phase and the resultant amplitude is zero.

d. As a result of this alternate reinforcement and interference, the two notes will at times swell in volume, and at other times they will be almost inaudible, thus producing beats. As seen from the figure, the frequency of these beats is equal to the frequency *difference* between the two tones. One cycle of the beat note is indicated in C by the contour or *envelope* connecting the peaks of the resultant wave. Actually, with the 90-cps and 100-cps tuning forks, a beat frequency equal to the difference, or 10 cps, is obtained.

e. The principle of beats also applies to alternating currents of different frequency. Two alternating currents can be combined in such a manner as to produce a beat or difference frequency between them. If the beat frequency is within the range of hearing (16 to 16,000 cps, approximately), it can be made audible by transforming it into sound waves, As an example, assume that an unmodulated 1,000-kc radio wave is received in a radio set, and that this signal is mixed with the output of an oscillator operating at a frequency of 1,001 kc. In figure 170, the r-f signal is at A and the oscillator output frequency at B. The resultant waveform is shown at C. It is generated by alternate reinforcement and cancellation as in the case of the two sound waves. The beat note, which is 1,001 kc minus 1,000 kc=1 kc, or 1,000 cps, is represented by the envelope of the resultant signal. If this signal is rectified as in D, and the r-f pulses are filtered out, only the 1,000-cps beat note remains, as in E. The electrical beat frequency then is passed through a loudspeaker or headphone, and becomes audible as a 1,000-cps tone. In principle, this is the process which takes place when a regenerative detector is used in the reception of c-w.

f. The reception of a modulated r-f signal in a superheterodyne receiver takes place essentially in the manner described above (fig. 171). A typi-

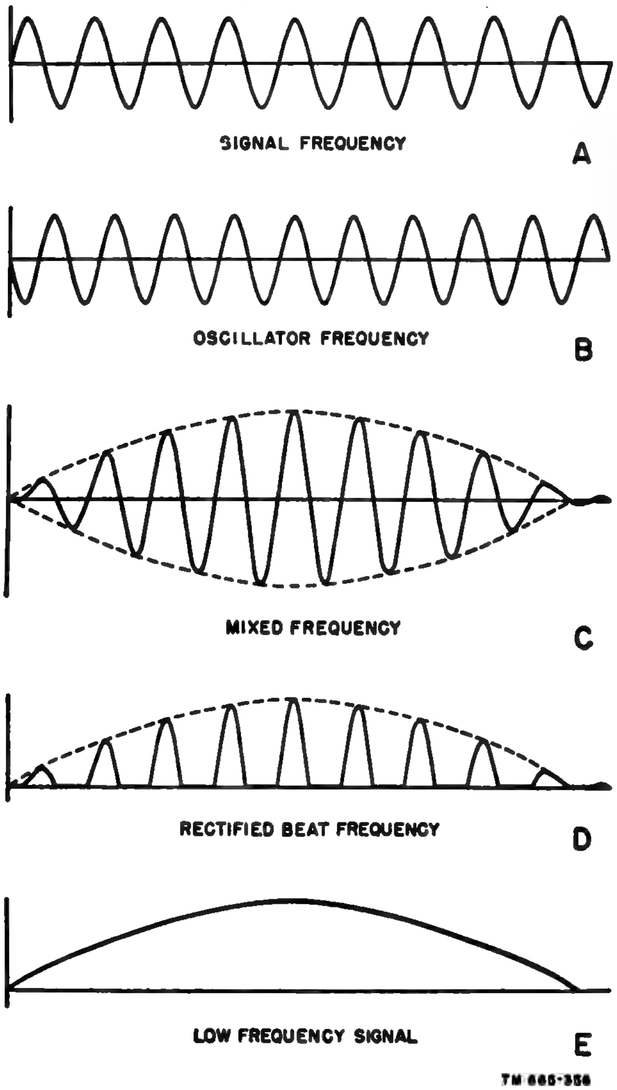

Figure 170. Superheterodyne reception of unmodulated (c-w) signal.

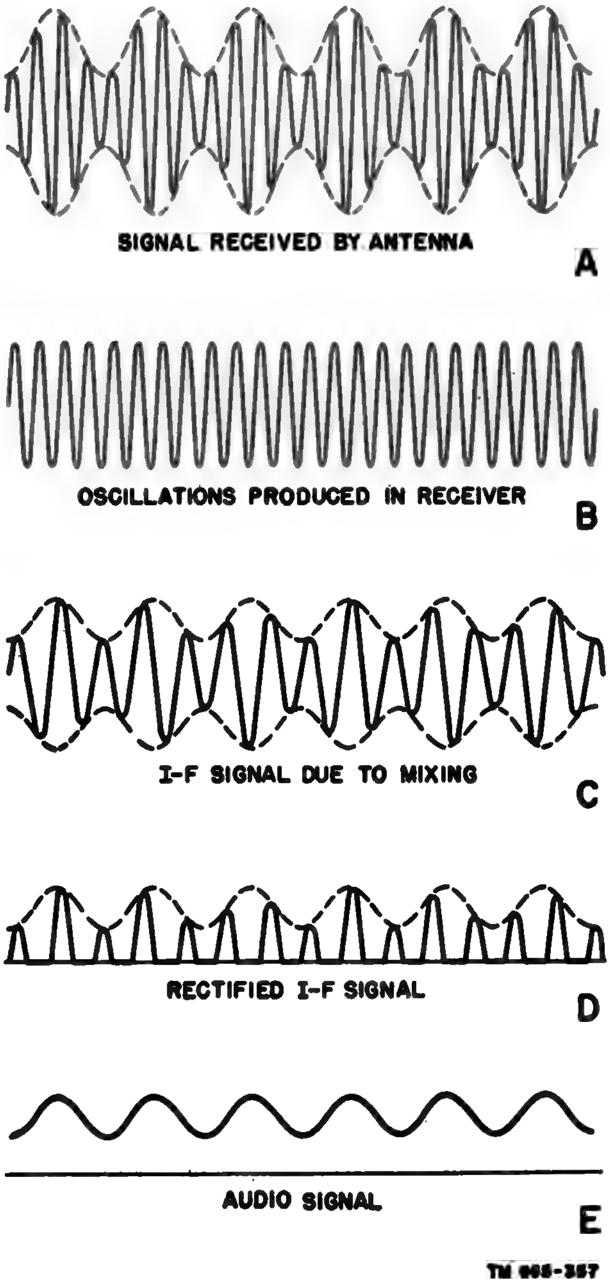

Figure 171. Superheterodyne reception of modulated r-f signal.

cal modulated r-f signal, intercepted by the receiver antenna shown in A, is amplified to a useful level with an r-f amplifier. In B, it is mixed with the output of a local oscillator which is a continuous wave of a frequency differing from the incoming signal frequency by an amount equal to the desired difference, or intermediate, frequency. It does not matter whether the frequency of the local oscillator is higher or lower than the r-f signal frequency, so long as the difference between the two is equal to the correct intermediate frequency.

g. For example, if the frequency of the incoming signal is 1,500 kc and the desired intermediate frequency is 455 kc, a common value, then the frequency of the local oscillator can be either 1,500 plus 455=1,955 kc, or 1,500 minus 455=1,045 kc. In either case, an i-f equal to the difference of 455 kc is produced. The intermediate frequency always is chosen well above the highest audio-frequency component in the desired signal, since otherwise considerable distortion of the desired intelligence would result. The result of mixing the modulated r-f signal with the output of the local oscillator is shown in C. An intermediate difference, or beat, frequency is generated as before. The amplitude of the beats, however, varies in this case as the amplitude of the modulated wave. In other words, the *envelope of the i-f (intermediate-frequency) signal reproduces the modulation of the received r-f signal.*

h. The higher-frequency modulated radio signal has been converted into a lower-frequency signal which carries the original modulation. The stage of the receiver which accomplishes this result is known as the *mixer* or *first* detector. The modulated i-f signal then can be amplified to the required level by one or more stages of i-f amplification. It is rectified and filtered in a conventional detector, as in D, sometimes called the *second* detector, so that only the audio modulation corresponding to the envelope of the rectified i-f signal remains, as in E.

124. Characteristic of Mixer

a. Two alternating currents of different frequency produce a beat frequency when they are combined in a suitable mixer. If two alternating currents differing in frequency are fed into a resistance load, *no resultant beat frequency is produced.* The two currents combine in a complex wave, but this wave has no new additional frequencies. As far as the resistance is concerned, each current is separate, and no interaction takes place because a resistance is a *linear* device; that is, the current flowing through it is directly proportional to the voltage across it (Ohm's law). The voltage-current characteristic of any linear device can be represented by a straight line, as in A of figure 172. The slope of the line is equal to E/I, or R.

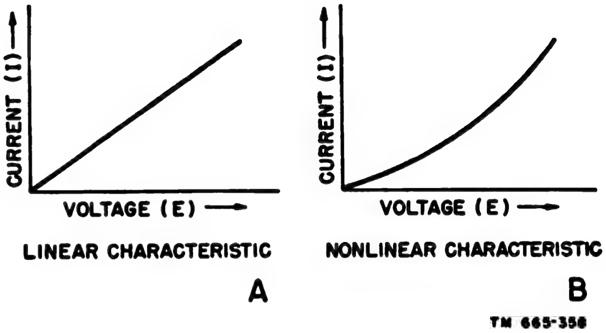

Figure 172. Required mixer characteristic

b. It is a fundamental fact that a device with a linear characteristic produces no interaction between currents of different frequency, and, therefore, no beat frequencies. Mathematical analysis shows that a *nonlinear* voltage-current characteristic, shown in B, leads to production of new frequencies in the output which are not present in the input. If two alternating currents of different frequency are impressed on a nonlinear device, they interact to produce a beat or difference frequency in the output. This is not the only additional frequency produced in the output of a nonlinear device. For example, if the output current of a device varies as the *square* of the applied voltage (such as in a square-law detector), the following prominent frequencies are produced as a result of applying two sine waves at different frequencies:

(1) The original frequencies of the applied alternating currents.
(2) Frequencies twice the value of the applied frequencies.
(3) A frequency equal to the *sum* of the original applied frequencies.
(4) A frequency equal to the *difference* of the two applied frequencies.

c. If the nonlinear device follows a more complex relationship between input and output, many additional frequencies also will be present in the output. For superheterodyne reception, only the sum or difference frequency is of interest, and all other frequencies in the output of the mixer must be filtered out. Many devices have a nonlinear voltage-current characteristic. One of the simplest is the ordinary vacuum tube when operated along the curved part of its characteristic curve.

125. Selectivity

a. The superheterodyne receiver provides much greater selectivity than any other type of receiver. The heterodyne principle assures a sufficient relative frequency separation, even for very closely spaced adjacent carriers. For example, assume that a desired signal of 4,000 kc and an undesired signal of 4,040 kc are both present in the input of the receiver. The actual separation between these signals is 40 kc, and the percentage of frequency separation is 4/400 times 100=1 percent. The tuned circuits of a trf receiver would have great difficulty in separating two signals with only a 1-percent relative frequency separation, and interference should be expected.

b. In a superheterodyne receiver, the situation is entirely different. Assume that the receiver has an intermediate frequency of 455 kc. To produce this difference frequency for an incoming signal of 4,000 kc, the local oscillator must be tuned to a frequency of 4,000 plus 455=4,455 kc. After mixing the two signals, the difference frequency, or i-f, is then 455 kc. The undesired signal of 4,040 kc also beats with the local oscillator to produce a difference frequency of 4,455 minus 4,040=415 kc. At the input to the i-f amplifier, which is tuned to 455 kc, both the 415-kc and the 455-kc beat frequencies are present. The *numerical* separation between these signals is still 40 kc (455 minus 415), but the percentage of frequency separation is now 40/455 times 100, or about 9 percent. The relative frequency separation between the two signals and the selectivity of the receiver, therefore, have been greatly increased.

c. It must be remembered that this relative improvement in selectivity is in addition to the gain in selectivity achieved by circuit improvements, which are discussed in a later paragraph. At the lower intermediate frequency, the losses in the tuned circuits of the superheterodyne are substantially lower than in a trf receiver. The resonance curve, therefore, is sharper, and the selectivity also is increased by this factor.

126. Basic Superheterodyne Receiver (fig. 173)

a. In the order in which a signal passes through the receiver, the basic stages for a-m superheterodyne reception are:

(1) An antenna for intercepting the signals from a transmitter.

(2) A variable-tuned r-f amplifier stage for selecting the desired signal. The r-f amplifier is not absolutely essential for superheterodyne reception, but its presence improves the signal-to-noise ratio and adds other desirable characteristics that will be discussed.

(3) A mixer in which the r-f signal is combined with the output of a local oscillator to generate an intermediate-frequency signal.

(4) A local oscillator for generating the signal which beats with the r-f signal. This can be any one of the conventional oscillators discussed in chapter 3.

(5) An i-f amplifier section consisting of one or more stages for amplifying the i-f signal from the mixer.

(6) A detector circuit for demodulating the i-f signal.

(7) An a-f power amplifier consisting of one or more stages for amplifying the audio-frequency output of the detector to a value sufficient to drive a loudspeaker or headphones.

(8) A loudspeaker or headphones for converting the electrical audio-frequency variations into sound waves corresponding to the original audio energy which modulated the r-f signal at the transmitter.

b. The fundamental operation of the superheterodyne receiver for the reception of a-m signals is as follows (fig. 173):

(1) Modulated r-f signals from many transmitters are intercepted by the antenna. They are coupled through an antenna input transformer to the first stage of the receiver, usually a variable-tuned r-f amplifier.

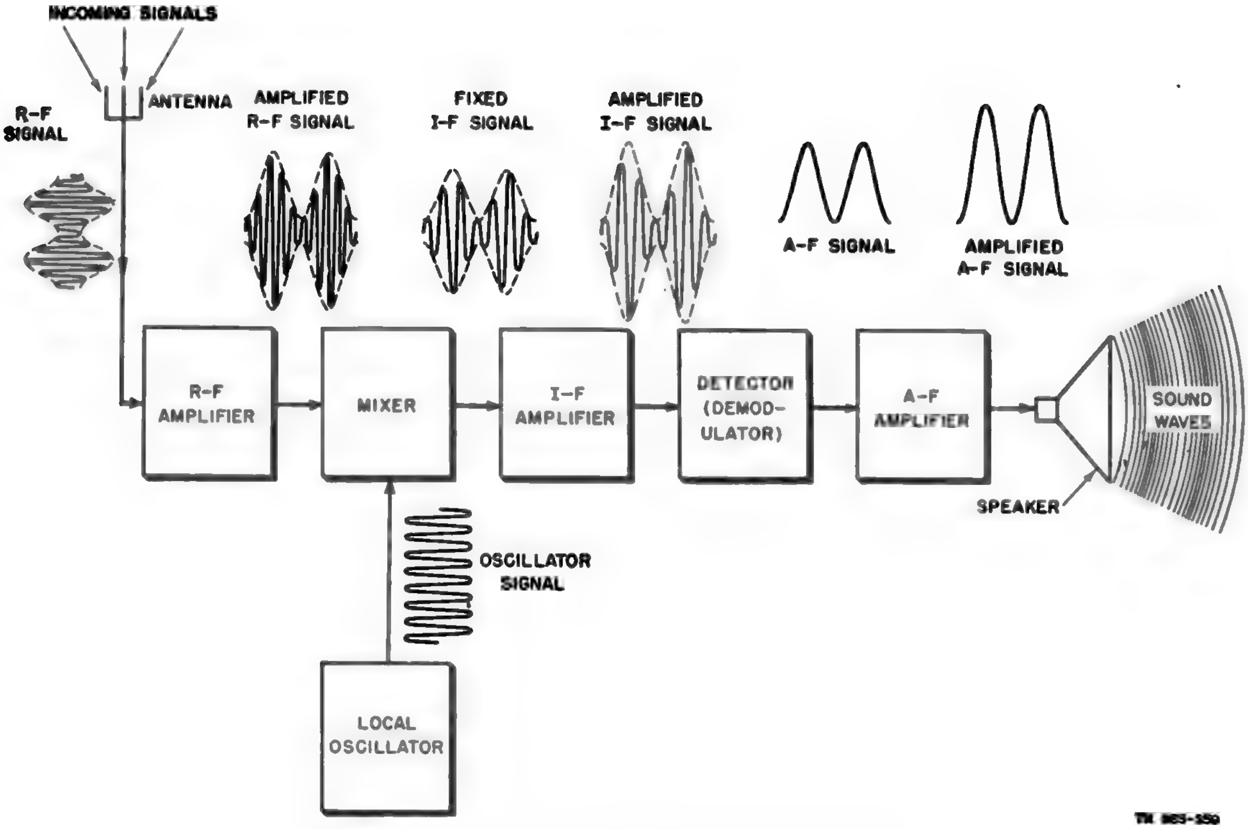

Figure 173. Block diagram of basic superheterodyne receiver.

(2) The desired r-f signal is selected by the tuned circuit of the r-f amplifier. This signal is amplified, and all other signals are rejected to some degree.

(3) The amplified r-f signal is coupled to the input of the mixer stage, where it is combined with the output of the local oscillator. In this process of heterodyning, a beat frequency equal to the difference between the r-f signal and local oscillator frequencies is produced. The frequency of the local oscillations is chosen either above or below (usually above) the r-f signal frequency by the required amount, so that the difference frequency is the desired i-f. The resulting i-f signal contains the *same modulation* as the original r-f signal.

(4) The i-f signal is amplified in the fixed-tuned i-f amplifier stages and is coupled to the input of the detector.

(5) The detector stage removes the audio modulation contained in the i-f signal and filters out the i-f carrier, which is no longer needed.

(6) The resulting audio signal is amplified to the level required for energizing an electromechanical reproducer.

(7) The electrical audio variations are converted into the corresponding sound waves by the reproducer (loudspeaker or headphones).

127. Frequency Conversion

a. General.

(1) The oscillator and mixer circuits together achieve the frequency conversion of an r-f signal to an intermediate frequency. Various methods and circuits exist for accomplishing this. All these arrangements are similar in that they use the nonlinear characteristic of a vacuum tube for mixing the r-f signal and local-oscillator frequencies. The plate current of the mixer tube is varied to produce a voltage of the desired intermediate frequency across the primary of a tuned i-f transformer. The secondary of this transformer is coupled to the grid of the first

i-f amplifier stage. The methods for frequency conversion differ chiefly in the types of tubes used and in the manner in which the signal and oscillator voltages are injected into the mixer tubes.

(2) Two methods are used to produce the desired frequency conversion. In one, a separate oscillator tube (usually a triode) is used to produce the local oscillations. The output of this tube is injected into another tube by some means of coupling. The incoming r-f signal also is injected into this second tube along with the local oscillations. The two signals can be injected into the second tube at the same point or at different points, where they combine to produce the intermediate frequency (among others) in the output. The tube in which the two signals are combined is called the *mixer*. The distinguishing feature of this method is that *two* separate tubes are used.

(3) In the second method only *one* tube, known as a *converter*, is used. The oscillator and mixer tubes are combined into a single tube which performs both functions. In the usual arrangement, the r-f signal is injected at one electrode, the local-oscillator signal being injected at some other electrode. There are also converter-tube types in which both signals are injected at the same electrode. The advantage of this method is that only one tube is necessary.

b. Terms.

(1) Certain characteristics are referred to when describing the performances of mixers and converters in frequency-conversion systems. One of these is the *conversion transconductance*, G_c, which is defined as the ratio between the i-f current in the output of the frequency converter and the r-f signal voltage,

$$G_c = \frac{\textit{i-f}\ \text{output current}}{\textit{r-f}\ \text{input voltage}}.$$

where G_c is in mhos (reciprocal of ohms) when the current is in amperes and the voltage in volts. G_c usually is in micromhos, which is mhos divided by 1,000,000. Representative values range from 300 to 950 micromhos. The conversion transconductance is an important quantity because the gain of the stage depends on the value of G_c; the higher this value the greater the gain.

(2) The amplification achieved in the frequency converter is called the *conversion gain*, or translation gain. It is defined as the ratio of the i-f output voltage to the r-f input voltage,

$$\text{Conversion gain} = \frac{\textit{i-f}\ \text{output voltage}}{\textit{r-f}\ \text{input voltage}}$$

This gain must be high in order to have amplified output from the tube. The conversion gain also can be shown to equal the conversion transconductance multiplied by the total load impedance on the tube. In order to have high gain, a tube with a sharp cut-off characteristic must be used.

(3) Another feature desired in frequency converters is control of amplification by means of a remote, or gradual, cut-off characteristic. This is in conflict with the need to have a sharp cut-off characteristic for high conversion gain. Therefore, either a compromise must be made, *or* a specially designed tube used which incorporates both remote and sharp cut-off characteristics.

(4) A high signal-to-noise ratio is another important desired characteristic. All frequency converters introduce a certain amount of noise, reducing the over-all signal-to-noise ratio of the receiver. Tube noise usually is measured in terms of equivalent grid resistance. The higher the noise produced, the higher the resistance. Tubes operated as converters have higher equivalent grid resistance than when the same tubes are operated as ordinary amplifiers.

(5) A highly desirable characteristic in frequency converters is that there be a minimum of interaction between the local-oscillator and r-f signal circuits. This interaction results in a change in oscillator frequency, called *pulling*, under certain conditions. In order that the local oscillator have maximum frequency stability, it is necessary to isolate it from the r-f signal circuits.

(6) Other desirable characteristics in frequency converters are low input conductance at high frequencies, high plate resistance, and minimum amount of space-charge coupling. All of these terms are discussed in connection with specific circuits for frequency conversion.

128. Simple Converter

(fig. 174)

a. Before the development of modern pentagrid converters, separate mixers and oscillators were used universally. Ordinary triodes and pentodes make excellent mixers, especially at high frequencies, and they still are used to a considerable extent.

b. The mixer tube functions as an ordinary plate detector biased approximately to cut-off. The tank circuit at the input of the mixer is tuned to the frequency of the incoming r-f signal. The oscillator grid tank circuit is tuned above (or below) the r-f signal frequency by an amount equal to the intermediate frequency. The i-f transformer in the plate circuit of the mixer is tuned to the desired difference frequency. The oscillator and mixer tuning capacitors are ganged together to permit single-control tuning.

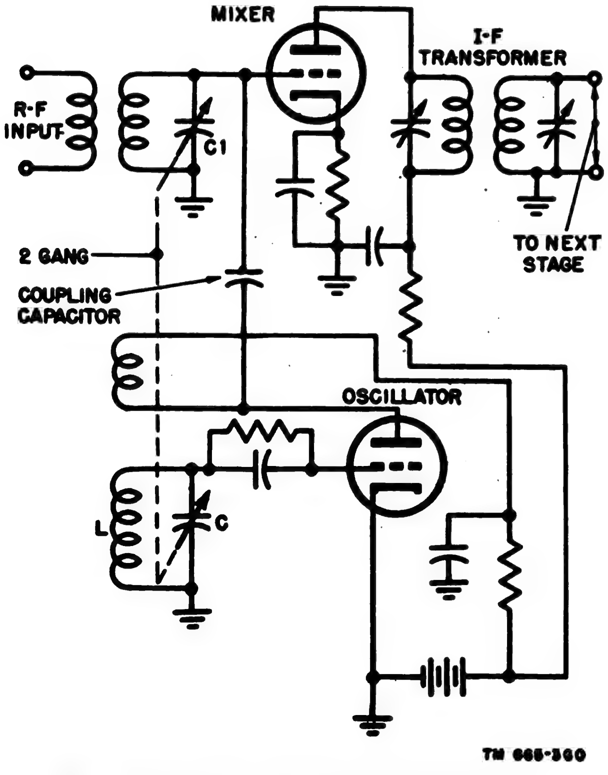

Figure 174. Triode oscillator and triode mixer.

c. A conventional tickler feedback oscillator is used in this frequency-converter circuit. Any other type also can be used as a local oscillator. For a properly designed mixer, very little power is drawn from the local oscillator. Oscillations from the plate circuit of the oscillator are coupled to the grid of the mixer by means of a coupling capacitor, a method known as *grid injection*. The oscillator voltage applied to the grid of the mixer tube should be as large as possible for maximum conversion gain. However, to avoid overloading, the sum of the oscillator and signal voltages impressed on the mixer grid should not exceed the grid bias. If the mixer is overloaded by driving the grid positive, both the gain and the input selectivity of the stage are reduced.

d. Any convenient means can be used to couple the oscillator voltage to the grid of the mixer tube. The amount of coupling should remain approximately constant as the oscillator frequency is varied so that the voltage injected at the mixer grid remains about the same over the frequency range. In figure 175, A and B illustrate two alternate coupling methods frequently used. In A, the oscillator output is inductively coupled to the cathode of the mixer. *Cathode injection* is very popular, because complete modulation of the mixer plate current is easily attained in this way. Both the oscillator signal coupled into the cathode circuit and the r-f signal injected into the grid circuit cause variations in the mixer plate current. The two different frequency components of the plate current beat together and generate the difference frequency (i-f). Interaction between the mixer and oscillator portions is somewhat less when cathode injection is used as compared with grid injection.

e. Inductive coupling between the oscillator and mixer is illustrated in B. The tank coil of a Hartley oscillator is directly coupled to the tank circuit in the input of the mixer. The method is equivalent to the capacitive grid injection in figure 174. If the oscillator coil is located too far from the mixer input, link coupling can be provided.

f. The simple plate-detector type of mixer performs very well and has the advantage of low cost. Its almost universal use in the early days of superheterodyne radios led to the name *first detector* for the mixer stage, a name still used occasionally to describe other types of mixers also. Mixers using triodes or pentodes are characterized by high conversion gain and good signal-to-noise ratio.

Their relatively low noise level makes them suitable for use at high frequencies. The chief disadvantage of triode or pentode converter circuits is the undesirable interaction caused by coupling between the mixer and oscillator portions. A strong interfering signal at the mixer input, whose frequency is close to the oscillator frequency, tends to make the oscillator synchronize, or *lock in*, with the interference, producing frequency instability. Pulling is especially annoying at higher frequencies where the local oscillator and signal frequencies differ by only a small percentage. The desire to isolate the local oscillator and r-f signal-input circuits from each other led to the development of *pentagrid* mixer and converter tubes.

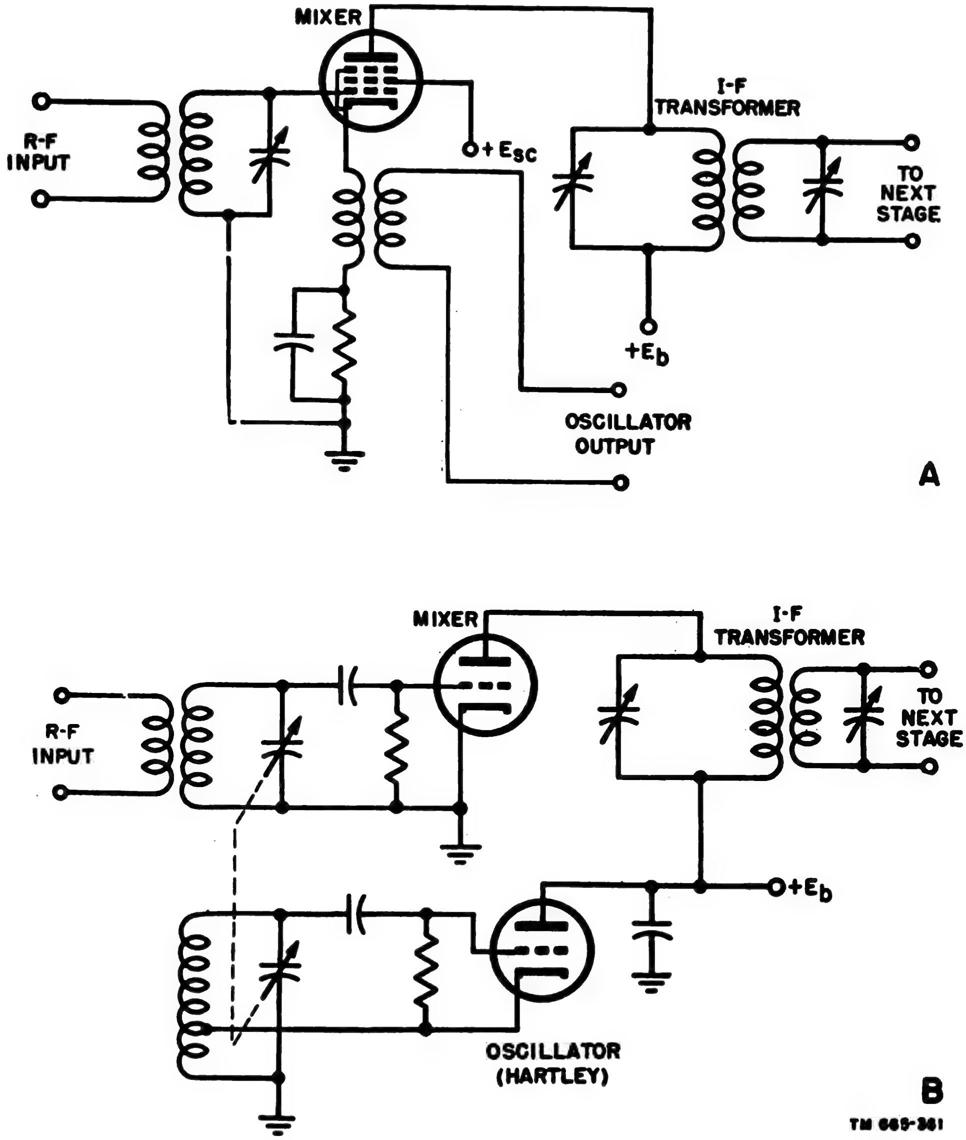

Figure 175. Simple frequency converters (showing different injection methods).

129. Pentagrid Mixer

a. Isolation of the local oscillator from the r-f input circuit is achieved in the *pentagrid mixer*, which is provided with *two* independent control grids, one for the r-f signal and one for the local oscillator signal (fig. 176). The tube contains a heater cathode, five grids, and a plate. Grids 1 and 3 are the control grids to which the r-f signal and oscillator voltages are applied, respectively. Grid 1, known as the *inner* grid, has remote cut-off (variable-mu) characteristic. Grid 3 is an injection grid used for modulating the electron stream in the tube. It has a sharp cut-off characteristic and produces a comparatively large effect on the plate current for a small amount of oscillator voltage. Grids 2 and 4 are screen grids which are connected internally. Their function is to accelerate the electron stream and shield grid 3 (oscillator signal grid) from the other electrodes. Grid 5 is a suppressor grid connected to the cathode, just as in ordinary pentodes.

b. The plate current of the pentagrid mixer is varied by the combined effect of the r-f and local oscillator signals. The r-f signal on grid 1 affects the electron stream as in an ordinary pentode. After being accelerated by grid 2, the electron stream is modulated by the oscillator voltage on grid 3. The arrangement is essentially the same as that of a suppressor-grid modulated amplifier (ch. 5). Excellent isolation of the oscillator section is achieved by the use of electron coupling and the two screen grids around the injection grid. Consequently, the r-f signal circuit has little effect on the oscillator frequency, and pulling is negligible. The addition of screen grid 4 and suppressor grid 5 also helps to increase the plate resistance and gain of the tube to a value similar to that of an ordinary pentode. With grid 3 biased approximately to cut-off in the absence of a signal voltage and an oscillator voltage sufficiently high to drive this grid positive, the conversion transconductance of the tube is about 300 micromhos, only a little less than for other types of converters. The d-c bias for grid 3 generally is obtained by a grid-leak resistance, whereas a cathode resistance is used to bias the signal grid 1.

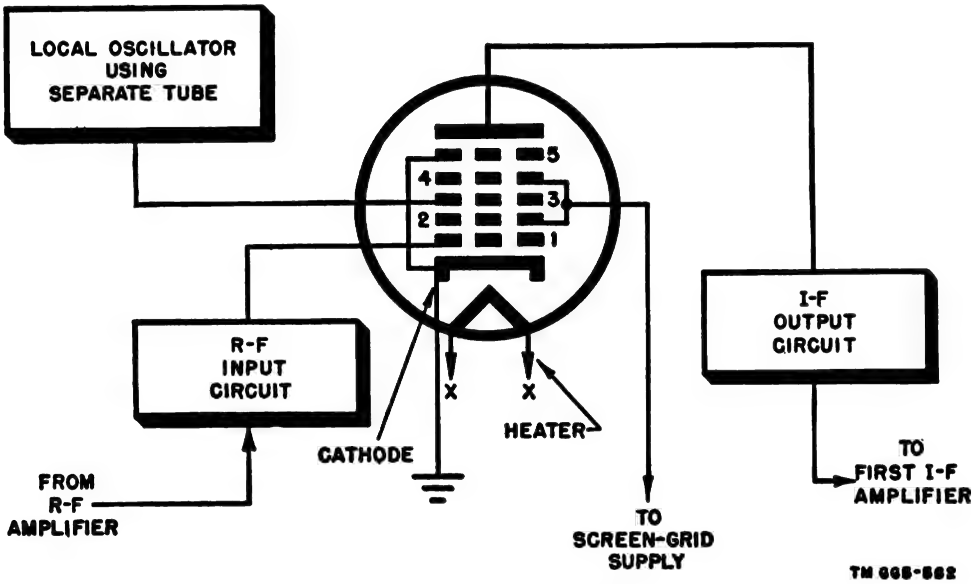

Figure 176. Pentagrid mixer.

c. Figure 177 shows a typical circuit of a pentagrid mixer with separate local oscillator excitation. The mixer input circuit is tuned to the frequency of the r-f signal, whereas the i-f transformer in the plate circuit is tuned to the difference frequency between the r-f signal and local oscillator frequencies. The local oscillator tuning capacitor is ganged with that of the signal input circuit so that the frequency difference between them always remains the same. The output of the oscillator is taken from the grid circuit and is applied to injection grid 3 of the pentagrid mixer through a coupling capacitor. This circuit frequently is used in the frequency stages of multiband and high-frequency superheterodyne receivers.

130. Triode Heptode
(fig. 178)

Some of the advantages of a separate oscillator and pentagrid mixer can be realized by a *triode-heptode* converter tube, which combines both in one envelope. An ordinary pentagrid mixer (heptode section) is built into the same envelope with a separate triode oscillator. The two sections share a common central cathode. The oscillator

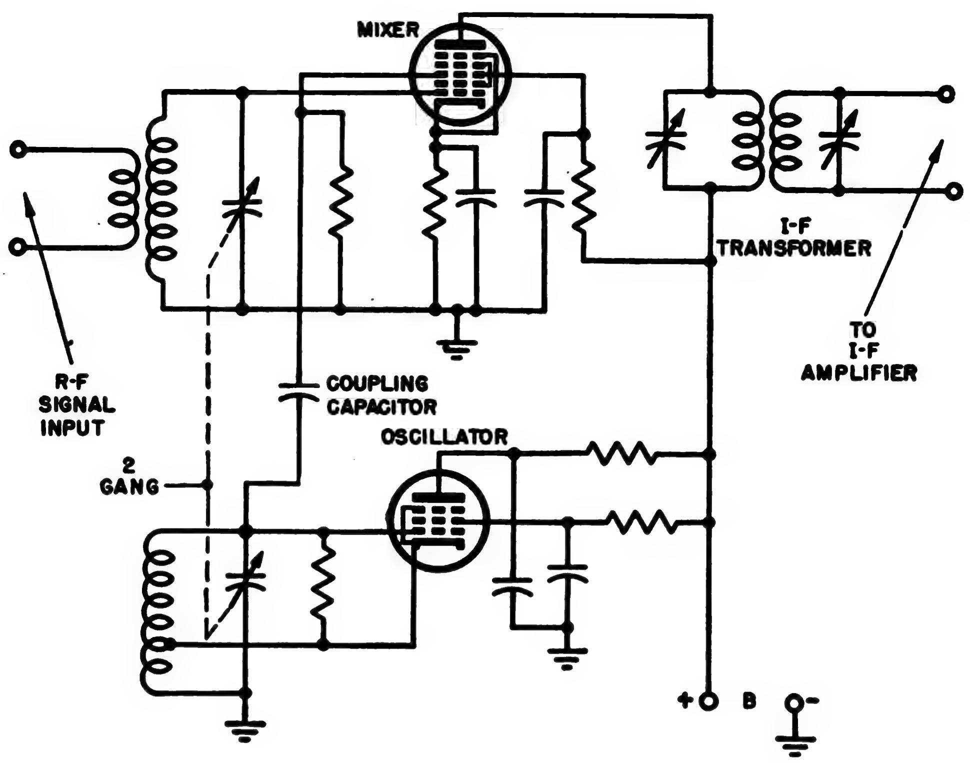

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Figure 177. Pentagrid mixer circuit.

grid is connected internally to the mixer injection grid 3. The oscillator section of the tube is mounted either above or below the mixer section. Because the oscillator uses a small portion of the cathode, its transconductance cannot be made high, and it does not function very efficiently. Other constructional limitations are present also. Triode-heptodes are used principally for compact portable receivers, where space is limited.

131. Triode Hexode
(fig. 179)

a. The constructional deficiencies of the triode heptode are largely overcome in *triode-hexode* converter tubes, which contain a triode oscillator and a hexode (four-grid) mixer in one envelope. The schematic representation and the actual electrode structure of triode hexodes are shown in A and B, respectively. The tube utilizes a special design and arrangement of the electrodes to provide an entirely separate electron stream for the mixer and oscillator sections, so overcoming the cathode-area limitation of triode heptodes. The cathode, triode grid, and triode plate form the oscillator section of the tube. The mixer unit consists of the cathode, hexode injection (triode) grid, hexode double screen grids, hexode signal grid, and the hexode mixer plate.

b. Grid 1 completely surrounds the cathode. The side toward the triode oscillator plate acts as the oscillator control grid, whereas the side facing

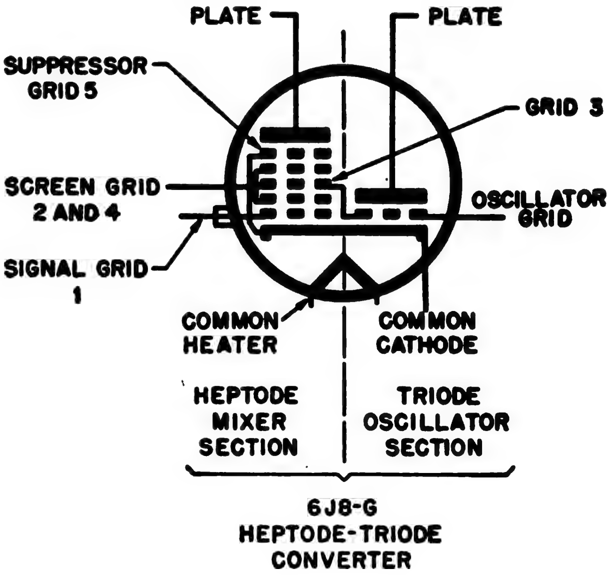

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Figure 178. Triode-heptode frequency converter.

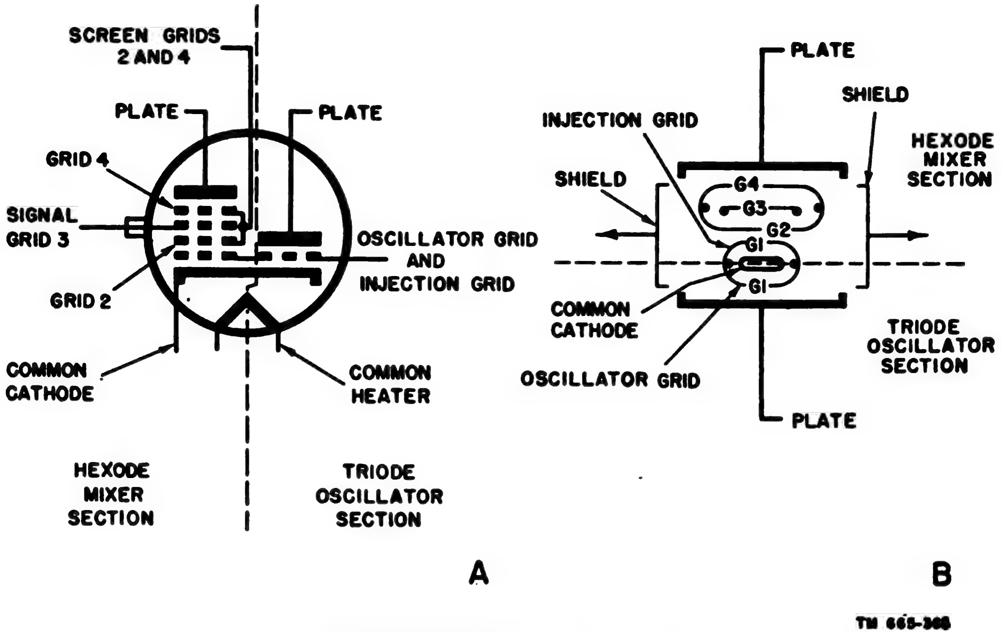

Figure 179. Triode-hexode converter.

the mixer section serves as the oscillator injection grid, modulating the electron stream at the oscillator frequency. Two metal shields at the sides, connected to the shell of the tube, prevent stray electrons from producing undesirable coupling between the mixer and oscillator sections. They also act as a suppressor for the hexode unit, and a suppressor grid therefore can be omitted. The action of the tube in converting an r-f signal to an intermediate frequency depends on the generation of the local oscillator frequency by the triode unit, the application of this frequency to the hexode injection grid, and the mixing of this frequency in the hexode unit with that of the r-f signal applied to the hexode signal grid.

c. A typical frequency-converter circuit using a triode-hexode tube is shown in figure 180. A tickler feedback circuit is used for the oscillator section. Its output is impressed on the mixer injection grid, and then it is mixed with the r-f signal applied to grid 3. The i-f transformer in the plate circuit of the mixer section is tuned to the beat frequency.

d. The triode-hexode mixer provides good isolation between the oscillator and mixer sections, and little pulling occurs. The conversion gain is about the same as for the previously discussed circuits, and it holds up well at high frequencies. These characteristics make the tube suitable for use in high-frequency and multiband superheterodyne receivers.

132. Pentagrid Converters

a. A pentagrid converter combines the functions of the oscillator and frequency mixer in a single structure, coupling between the two units being obtained by the common electron stream. The electrode structure of an early type of pentagrid converter is shown in A of figure 181, and its connection to the external circuits is illustrated in B. Five grids are utilized. The cathode, grid 1, and grid 2 are connected to an external circuit to function as an ordinary triode oscillator. Grid 1 is the grid of the oscillator, and grid 2, consisting simply of two vertical rods placed in the electron stream between grids 1 and 3, is its plate.

b. The oscillator grid varies the intensity of the electron stream from the cathode and causes it to pulsate at the oscillator frequency. Most of the electrons from the cathode bypass the two positive oscillator plate rods (grid 2) and go on to screen grid 3, which accelerates the electron stream and serves as an electrostatic shield. Some of the electrons strike the screen and cause secondary emission, but most pass through its openings toward the r-f signal grid 4, which is biased negatively at all times. Thus a space charge of retarded electrons is formed betweeen grids 3 and 4. This space charge constitutes a *virtual cathode* for supplying the mixer section of the tube. This virtual cathode in front of grid 4 forms with each pulse of space current and then dis-

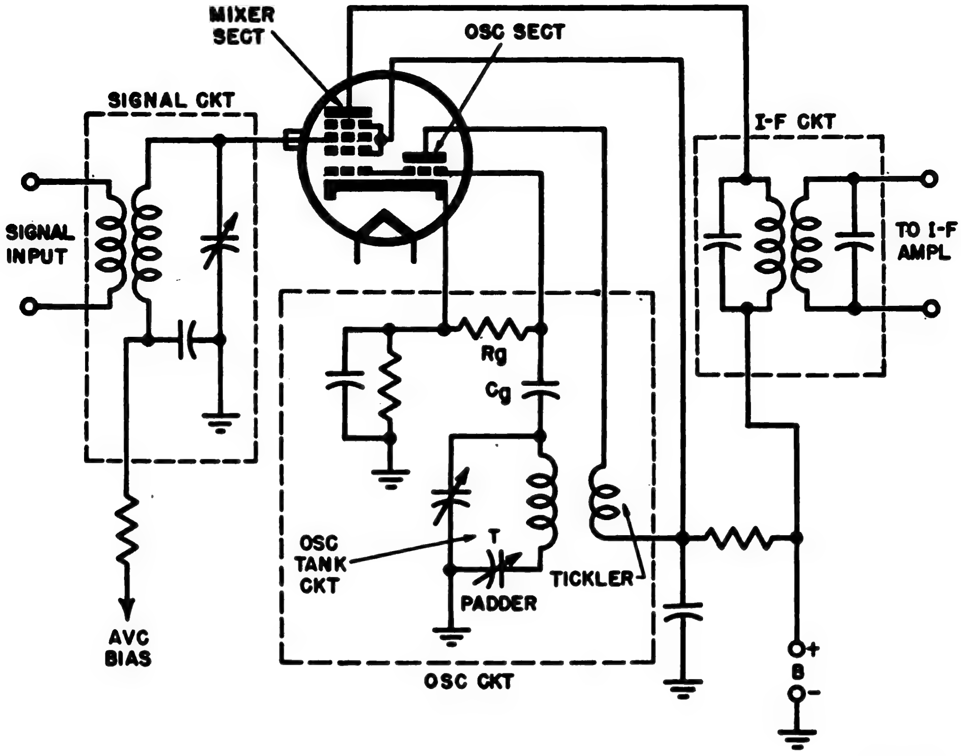

Figure 180. Triode-hexode frequency-converter circuit.

appears between the oscillator pulses; therefore, it supplies the rest of the tube with an electron stream that varies at the oscillator frequency.

c. The number of electrons that the plate is able to draw away from this pulsating virtual cathode depends on the r-f signal voltage applied to grid 4. As a result, the electron current actually arriving at the plate is modulated by both the oscillator and the signal voltages, and the two voltages are effectively mixed in the output of the tube. Because of the nonlinear characteristic of the mixer, sum and difference frequencies appear in

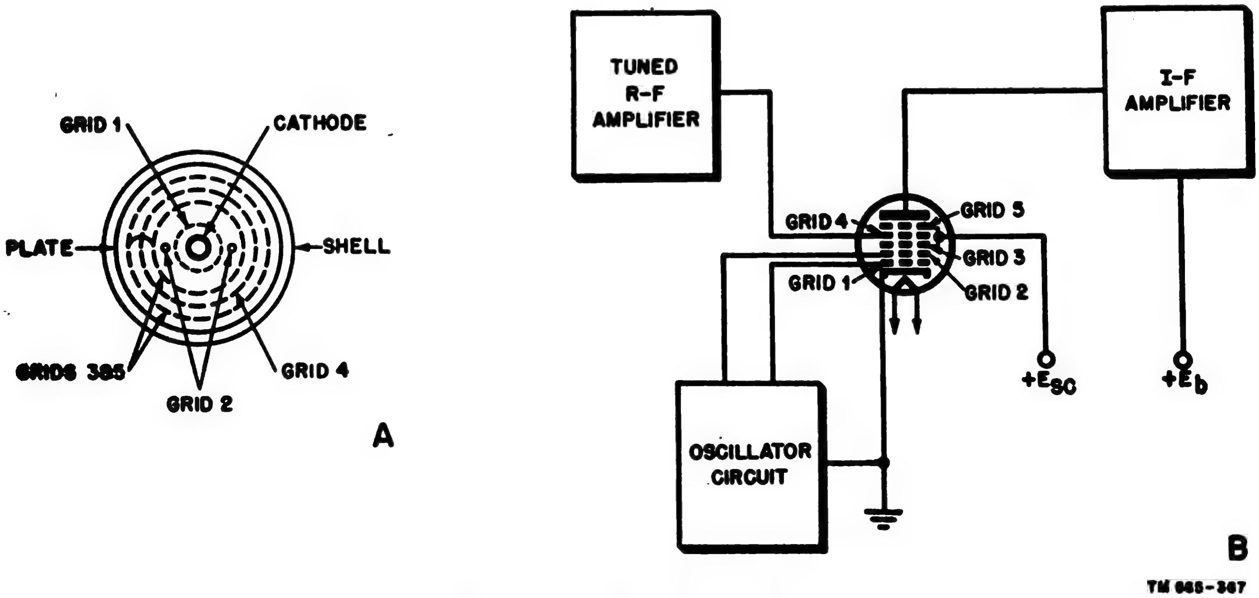

Figure 181. Pentagrid converter.

the plate current of the tube. The difference frequency is selected by the tuned i-f transformer.

d. Between the r-f signal grid and the plate of the tube is placed another screen, grid 5, which is connected internally to screen grid 3. Grids 3 and 5 together accelerate the electron stream and electrically shield signal grid 4 from the other electrodes. Grid 5 also severs to make the plate current substantially independent of the plate voltage, and so gives the pentagrid converter a high plate resistance of the same order as that obtained in ordinary pentodes. Signal grid 4 of the pentagrid converter usually has a remote cut-off characteristic. This makes it possible to control the conversion transconductance, and consequently the gain, by varying the bias on this grid.

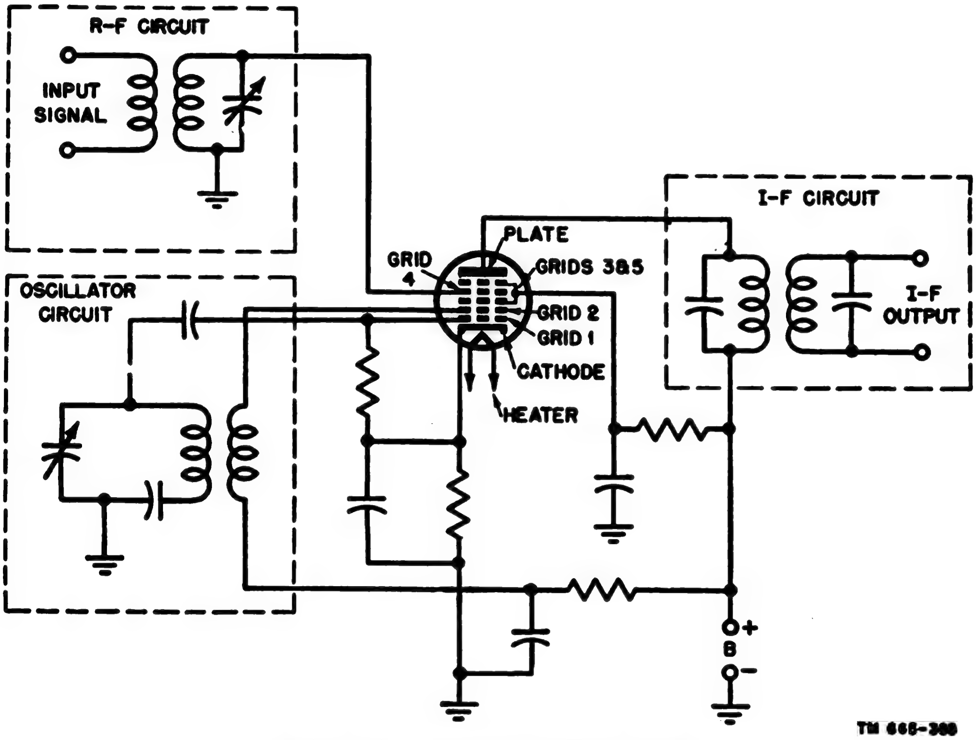

Figure 182. Pentagrid converter circuit.

e. The incoming r-f signal shown in the general circuit arrangement of the pentagrid converter (fig. 182) is selected by the tuned input circuit and is applied to signal grid 4, so that it modulates the electron stream. The local oscillator consists of a simple tickler feedback circuit. The oscillator frequency is controlled by the variable capacitor in the oscillator tank circuit. This capacitor is ganged with the signal input tuning capacitor in such a manner that it maintains a constant frequency difference equal to the desired i-f. The cathode resistor provides grid bias for the tetrode mixer portion of the converter; grid-leak resistance provides separate bias for the oscillator portion. This permits optimium biasing for the oscillator and mixer sections. The i-f transformer in the output selects the correct difference-frequency component of the plate current of the converter. This component is coupled to the succeeding i-f amplifier.

f. Pentagrid converters of the type discussed operate satisfactorily at medium frequencies, but their performance becomes increasingly poor at higher frequencies. This is caused chiefly by falling off in oscillator output as the frequency is raised and increasing interaction between the mixer and oscillator portions. Undesirable coupling between the mixer and oscillator sections appears, in spite of the two screen grids, because of a residual capacitance between grid 4 and the space charge of the virtual cathode (called *space-charge coupling*). Since the space charge pulsates at the oscillator frequency, the residual coupling causes currents at the oscillator frequency to flow from grid 4 through the tuned r-f input circuit.

g. Recent types of pentagrid converter tubes are designed to minimize the interaction between the signal grid and the oscillator plate by means of special construction of the oscillator section. The shaping, spacing, and number of turns on the grids are modified, and additional collector plates are introduced. As a result, the space charge around the cathode is unaffected by the signal grid. In addition, the arrangement of the electrodes has been changed so that no electrode functions solely as the oscillator plate (fig. 183). Grid 1 functions as the oscillator grid. Grid 1 is connected to screen grids 2 and 4, both acting as the oscillator plate. The r-f signal grid 3 is shielded electrostatically by grids 2 and 4. Grid 5 functions as the suppressor. Pentagrid converters of this type operate well to frequencies as high as the f-m band (88 to 108 mc), but have high noise levels as compared with mixer-oscillator circuits.

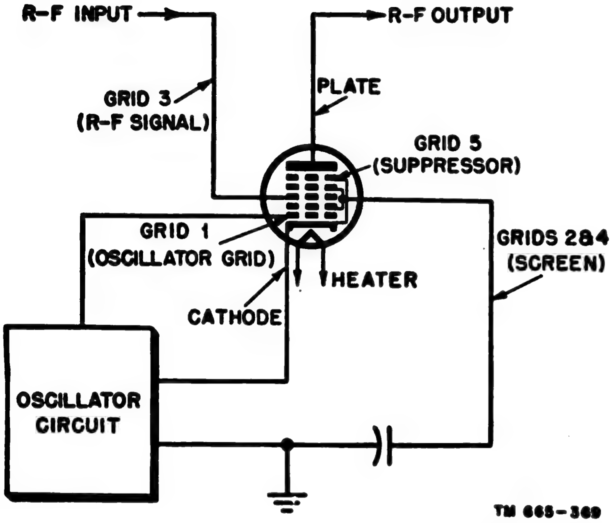

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Figure 183. Pentagrid converter circuit with r-f input to grid 3.

133. Frequency Tracking

a. The mixer and oscillator circuits of a superheterodyne are said to *track* when they maintain a constant frequency difference (the i-f) between them throughout the tuning range. Since the oscillator circuit is generally set to a frequency higher than that of the mixer and r-f circuits, the capacitance and inductance of its tuned circuit must be smaller. Also, for the higher oscillator frequency, the *percentage* of frequency shift for the oscillator tuning capacitor must be smaller for the same tuning range than that of the mixer and r-f capacitors. This is achieved in some receivers by using a smaller coil and a smaller tuning capacitor with specially shaped plates in the oscillator circuit. The special shape of the plates insures tracking throughout *one* frequency band. This method cannot be used, however, in multiband receivers, since each band requires a differently shaped oscillator tuning capacitor.

b. More commonly, the same size tuning capacitors are used for both oscillator and mixer circuits. The required frequency difference then is made up with a smaller oscillator coil, and tracking is attained with *trimmer* and *paddler* capacitors. The trimmer is connected in parallel with the oscillator tuning capacitor, and the padder is connected in series with it (fig. 184). At the *high-frequency* end of the tuning range, the oscillator tuning capacitor is set for minimum capacitance. The parallel trimmer has about the same order of magnitude as this minimum value and its adjustment determines the proper resonant frequency at this end of the frequency range.

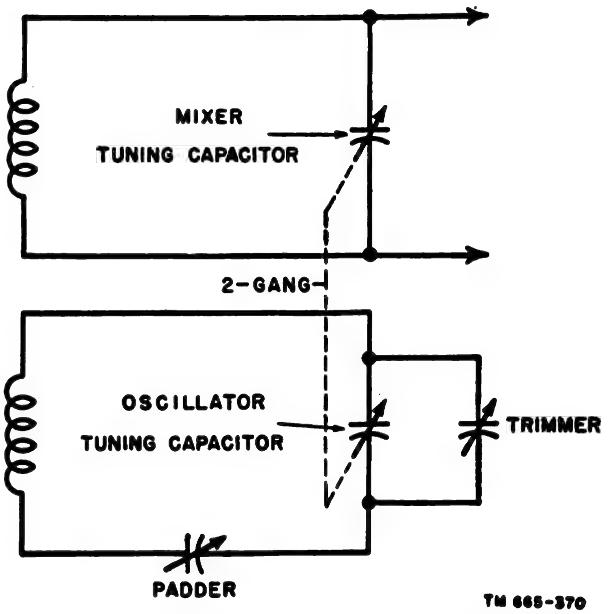

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Figure 184. Padder and trimmer connections.

c. At the *low-frequency* end of the tuning range, the capacitance of the oscillator tuning capacitor is near maximum, and therefore the small parallel trimmer is negligible in comparison with it. Now, however, the series padder is comparable in magnitude to the main tuning capacitor and affects the resonant frequency. The value of the padder is usually about two to four times the magnitude of the maximum oscillator tuning capacitance. Since the total capacitance of two series capacitors is influenced chiefly by the *smaller* of the two capacitors, the effect of the series padder on the total tuning capacitance at the low-frequency end is not very great, but suffices to set the resonant frequency within the limits required for proper tracking. By proper adjustment of the padder and trimmer capacitors reasonable tracking accuracy can be attained throughout the frequency range. If several bands are utilized, a separate trimmer and padder capacitors usually are provided for each band.

134. Oscillator Stability

a. The circuits used as local oscillators in superheterodyne receivers must have a high degree of frequency stability. Obtaining the required frequency stability is a major problem in the design of the receiver, particularly where the receiver is to operate under conditions of wide temperature variation, high humidity, or severe mechanical vibration. Oscillator stability for higher-frequency receivers is a particularly difficult problem and sometime crystal oscillators are used. If the frequency of the oscillator is incorrect, the resultant intermediate frequency is no longer in the center of the pass band of the i-f amplifier. As a result, when an amplitude-modulated wave is being received, considerable distortion will occur. When very selective i-f amplifiers are used, the signal may be lost altogether.

b. Frequency variations of the local oscillator can be divided into long-time and short-time effects. Long-time changes or slow oscillator drift produces the greatest variation in frequency. This drift usually is produced as the result of heat and humidity affecting the constants of the tuned circuits and the oscillator tube. Short-time variations are caused by power-supply voltage variations, interference from power lines, and coupling from other stages, especially the mixer.

135. Intermediate-frequency Amplifier

a. The intermediate-frequency amplifier is of special importance in superheterodyne receivers because it controls, to a major extent, the selectivity and gain of the complete receiver. The amplifier contains from one to three tuned stages and utilizes high-gain pentode tubes in each stage. Operating only at the i-f frequency, the tuned circuits of the amplifier can be adjusted permanently for optimum amplification and selectivity. No variable tuning or tracking problems are met in the i-f amplifier.

b. In addition to providing high gain and sufficient selectivity between adjacent channels, the i-f amplifier must have the required fidelity to preserve intact the intelligence superimposed on the carrier at the transmitter. It will be remembered that amplitude modulation of a carrier generates side-band frequencies numerically equal to the carrier frequency plus and minus the highest modulation frequency present. For example, if modulation containing audio frequencies up to 5,000 cps is to be reproduced faithfully, the receiver must be capable of amplifying equally all frequencies in a band from 5,000 cps below the carrier frequency (lower side band) to 5,000 cps above the carrier (upper side band). This means that the i-f amplifier must pass uniformly a band of frequencies 10 kc wide.

c. The design of the tuned circuits in the i-f amplifier determines the band-pass characteristics. The tuning or selectivity of the i-f transformers must not be so sharp as to cut a portion of the lower and upper side bands containing the modulation. A 10-kc band generally is considered sufficient for reasonably faithful reproduction of speech and music. Much narrower bandwidths often are used for military communications, where a compromise between intelligibility and rejection to adjacent interference signals and noise is desired.

136. I-F Tuning

a. Coupled Resonant Circuits.

(1) Coupling in i-f amplifiers generally is obtained by using two coupled resonant circuits. A of figure 185 shows such a circuit, including the primary and secondary circuit resistances, R_p and R_s, respectively, which are chiefly associated with the coils. The resonant response of such a coupled circuit depends primarily on the degree of coupling—that is, the amount of mutual inductance, M, between the primary and secondary of the transformer. Typical resonance curves of two coupled resonant circuits for various degrees of coupling are illustrated in B. These curves have been obtained by plotting the current in the secondary of the

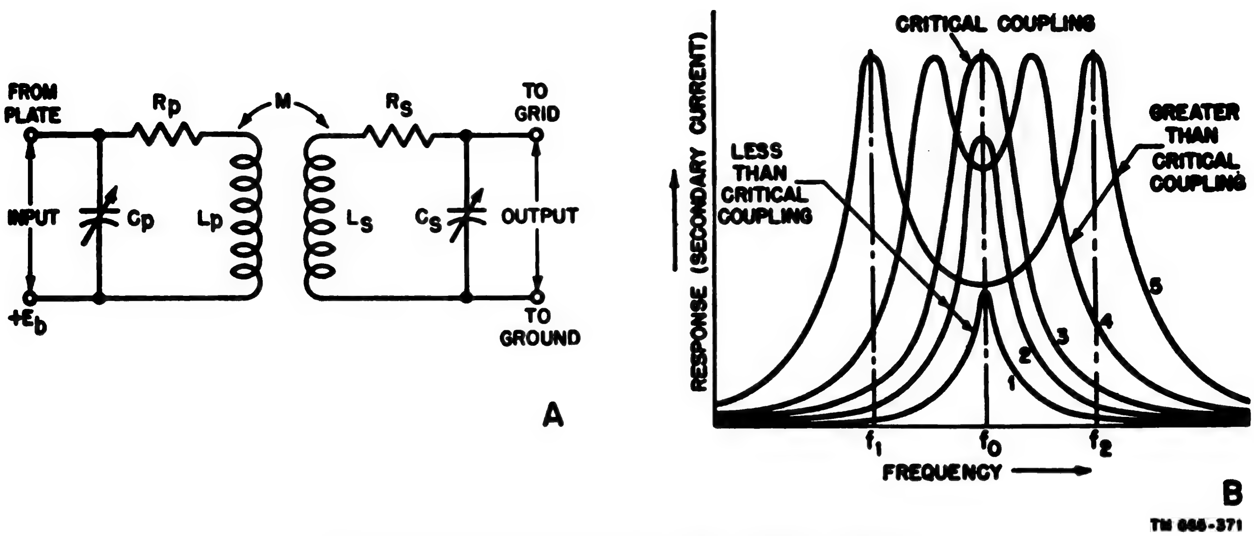

Figure 185. Characteristics of coupled resonant circuits.

transformer against frequency for constant input voltage to the primary, and with both circuits tuned to the same resonant frequency, f_o. When the coupling between the primary and secondary is quite loose, the secondary current, and consequently the secondary voltage, are small, but the resonance curve is sharply peaked (curve 1) and the selectivity is good. As the coupling is increased somewhat, the secondary current peak becomes larger, and the resonance curve becomes broader (curve 2). This tendency continues with increased coupling until the secondary current reaches its maximum possible value for a critical degree of coupling (curve 3).

(2) *Critical coupling* occurs when the resistance reflected back into the primary by the secondary current is equal to the primary resistance. (For explanation of reflected resistances, see paragraph 21*e*.) For this condition, the coefficient of critical coupling, k, is found to be

$$\text{critical } k = \frac{1}{\sqrt{Q_p Q_s}}$$

where

$$Q_p = \text{primary circuit } Q = \frac{2\pi f L_p}{R_p}$$

$$Q_s = \text{secondary circuit } Q = \frac{2\pi f L_s}{R_s}$$

If the primary and secondary circuit Q's are equal, as is often the case, then $Q_p = Q_s = Q$, and the coefficient of critical coupling

$$\text{critical } k = \frac{1}{Q}$$

The coefficient of critical coupling is usually very small, because Q is generally high. For Q's of 100, for example, the coefficient of critical coupling is 1/100, or .01.

(3) When the coupling is increased beyond the critical value, the secondary current curve begins to display *two* humps; this is known as *double-peaking* (curve 4). The magnitude of these two peaks is the same as that obtained for critical coupling. As the coupling is increased still further, the two peaks begin to spread apart in frequency, and the valley or dip between the peaks becomes more pronounced (curve 5). For extremely tight coupling, the response between peaks may go almost to zero.

(4) The reason for the appearance of the two humps can be understood by considering the impedance reflected back from the secondary to the primary of the transformer. The impedance coupled into the primary increases as the square of the mutual inductance, M. Above critical coupling, it becomes the major factor determining the total primary impedance. At the resonant frequency, the coupled impedance is purely resistive, and there-

fore lowers the Q of the primary circuit. At frequencies below resonance, the coupled impedance is largely inductive; therefore, it cancels out part of the primary series impedance, which is capacitive below resonance. At some frequency f_1 below resonance, therefore, the coupled reactance completely neutralizes the primary reactance, and the total primary impedance becomes very low. For this condition the primary current is very large. This large primary current, in conjunction with the high degree of coupling, induces a large voltage in the secondary, and so results in a correspondingly large secondary current. This accounts for the secondary current peak below resonance.

(5) At frequencies above resonance, the coupled impedance is largely capacitive, and it therefore neutralizes part of the primary series impedance, which is inductive above resonance. At some frequency f_2 above resonance, the primary impedance again reaches a minimum, and the primary current becomes very large. This induces a high secondary voltage, which in turn results in a large secondary current. This is the reason for the secondary current peak above resonance. If the coupling is below the critical value, the coupled-in impedance is not sufficiently great to cause the separate current peaks, but it does help to broaden the resonance curve.

(6) The double-peaked characteristic is taken advantage of in i-f transformers to obtain the required band-pass characteristic. By slightly overcoupling the coils of an i-f transformer (larger than critical k), the secondary current will be approximately constant near resonance over a range of frequencies between the two peaks (from f_1 to f_2, in B, fig. 185). Beyond these two frequencies, f_1 and f_2, the response falls off very rapidly, and the selectivity for adjacent channels outside the passband is excellent. If the required bandwidth is large, the coupling must be very tight to spread the two peaks sufficiently far apart. For this condition, however, the dip between the peaks becomes very pronounced, as indicated by curve 5 in B.

(7) Two methods are in use to smooth out this dip. One method (A of fig. 186) consists of *loading* the circuit by connecting a resistance in parallel with the resonant circuit. This damps out the resonant voltage rise and pushes the peaks down near the valley level. The result is a smoother response at the sacrifice of voltage gain in the transformer. The second method, in B, consists of filling in the dip with a single-peaked resonance curve of the proper characteristics. For example, the first i-f stage may have an overcoupled i-f transformer, which produces two peaks spaced the desired bandwidth apart. The i-f transformer of the second stage then can be designed so that its response fills in exactly the dip produced by the first stage. This is attained by less than

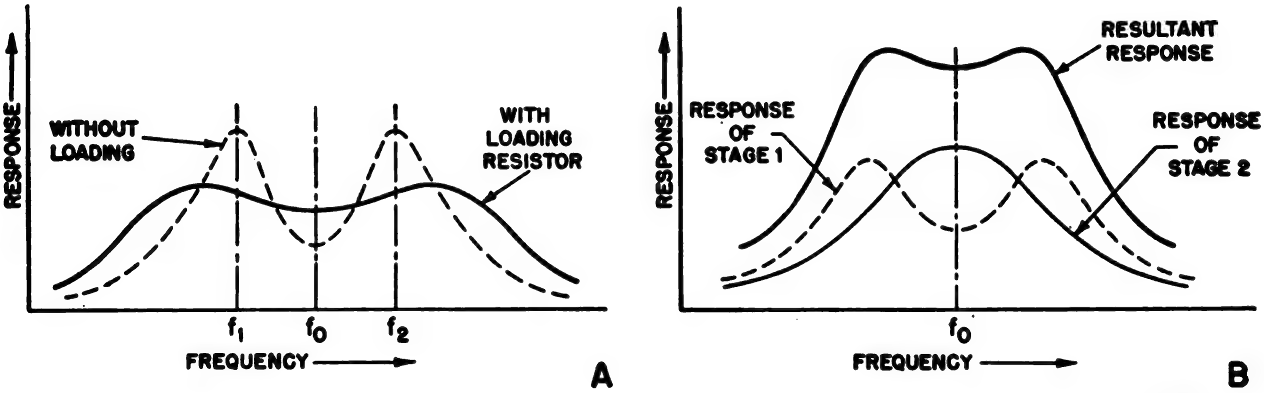

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Figure 186. Two methods of smoothing out dip. A. Effect of loading. B. Combined response of two i-f stages.

critical coupling in the second i-f transformer and with a Q of about one-half that of the first i-f transformer. The resultant response of the two stages is the product of the response of each stage and can approach the ideal *flat-topped* characteristic.

(8) Frequencies f_1 and f_2 of the two current peaks for values of coupling greater than critical are given by the following relations

$$f_1=\frac{f_o}{\sqrt{1+k}}$$

and

$$f_2=\frac{f_o}{\sqrt{1-k}}$$

where

f_o=the resonant frequency of the tuned circuits

k=coefficient of coupling (greater than critical).

The bandwidth over which the response is relatively uniform is then the difference f_2 minus f_1. It can be computed from the preceding relations, or directly by the approximation

$$\text{bandwidth}=f_2-f_1=f_o.$$

The relative bandwidth usually is expressed as the fractional deviation from the resonant frequency; that is,

$$\text{relative bandwidth}=\frac{f_2-f_1}{f_o}=k.$$

(9) For example, assume that both primary and secondary of the i-f transformer (A of fig. 185) are tuned to 455 kc, and that R_p=10 ohms, L_p=350 microhenries, R_s=14 ohms, and L_s=490 microhenries. What is the coefficient of critical coupling? If the *actual* coefficient of coupling is .02, what is the bandwith and the highest modulating frequency that is passed satisfactorily by the transformer? The primary circuit

$$Q=Q_p=\frac{2\pi fL_p}{R_p}=\frac{2\times3.14\times455{,}000\times350\times10^{-6}}{10}=100$$

The secondary circuit

$$Q=Q_s=\frac{2\pi fL_s}{R_s}=\frac{2\times3.14\times455{,}000\times490\times10^{-6}}{14}=100$$

Since $Q_p=Q_s=100$, the *critical* $k=1/Q=1/100=.01$. The actual $k=.02$; that is the circuit is overcoupled. For this condition the bandwith is approximately

$$f_ok=455\times.02=9.1 \text{ kc.}$$

Since there are two side bands containing the modulation, the highest modulating frequency is one-half the total bandwith, or 9.1/2=4.55 kc or 4,550 cps. This fidelity is satisfactory for general communications.

(10) Instead of overcoupling the primary and secondary of an i-f transformer, a double-peaked resonance curve also can be obtained by tuning the primary and secondary to slightly different frequencies with the coupling less than critical. The primary and secondary each will respond best to the frequency to which it is tuned. This type of tuning is known as *stagger tuning*, and it is used often to attain the required bandwidth instead of overcoupling the circuits.

b. Construction of I-F Transformer. The i-f transformer circuits are contained in a metal-shield container in which the coils and tuning capacitors are mounted. The capacitors can be made of mica, or they can be air trimmer capacitors. The coils may have an air core, or a powdered-iron core, the latter providing somewhat greater Q. Powdered-iron cores can be tuned by moving the core in or out of the coil, thus varying the inductance. This is called *permeability*, or *slug*, tuning. With permeability tuning, a fixed mica capacitor can be used. The frequency stability of permeability tuning is comparable to that of variable-tuned air capacitors. Stability is important to prevent frequency drift, which reduces the gain and selectivity of the i-f stage. Small protruding adjusting shafts permit tuning the transformer outside of the case.

137. I-F Circuit

a. In the typical circuit arrangement of an i-f amplifier in figure 187, only one stage is shown, since a second stage would simply duplicate the circuit of the first. I-f amplifiers contain from one to three stages, each with a pentode amplifier tube, but two stages generally provide all the gain that can be utilized. Pentodes usually are used for

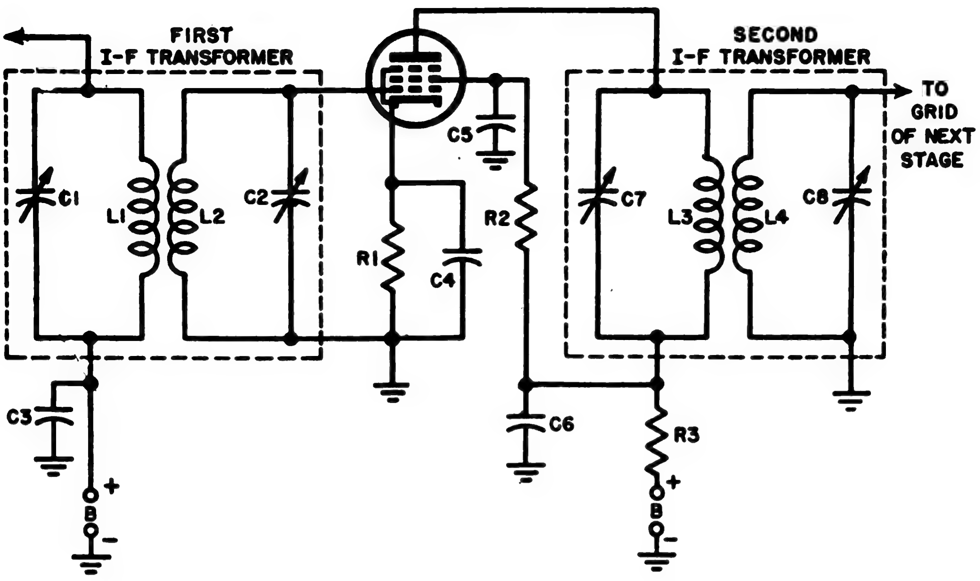

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Figure 187. Typical i-f amplifier circuit (one-stage).

high gain. They are generally of the remote-cut-off type, to permit control of the gain.

b. The first i-f transformer consists of a primary circuit connected to the mixer output, and a secondary circuit connected to the control grid of the pentode. Both primary and secondary are tuned to the intermediate-frequency output provided by the mixer. Single-tuned i-f transformers with an untuned primary sometimes are used, with a consequent loss of selectivity. Resistor *R*1 and capacitor *C*4 in the cathode of the tube provide the required bias on the tube. *C*5 is the screen bypass capacitor for r-f. Resistor *R*3 and capacitor *C*6 form a decoupling filter for isolating the amplifier from the common power supply, and so prevent feedback from the later stage to the earlier stage.

c. The plate of the pentode is connected to the primary of the second i-f transformer, which consists of *C*7 and *L*3. The primary is coupled to the secondary, *L*4 and *C*8, which forms the input circuit of the next stage. This can be another identical i-f amplifier, or the detector stage. If two or three i-f stages are used, careful shielding, bypassing, and circuit layout are necessary to prevent stray coupling, which can cause instability and oscillation. Occasionally, multiple-tuned circuits and additional i-f stages are used principally for the contribution which the additional tuned circuits make to skirt selectivity of the over-all response characteristic of the receiver; gain then becomes of secondary importance.

138. Selectivity of I-F Amplifier

The selectivity of each stage depends on the *Q* and the coupling of the i-f transformer, which already has been discussed. The *over-all* selectivity of the i-f amplifier is proportional to the number of tuned circuits (i-f transformers) utilized. The total selectivity increases as the product of the number of stages, in a manner similar to that for the tuned r-f amplifier. Over-all selectivity also increases if the intermediate frequency used is lowered. The exact i-f amplifier selectivity of military receivers varies widely, depending on the specific use to which the receiver is placed. Most communication receivers have variable i-f selectivity. A switching arrangement permits several amounts of fixed selectivities to be obtained. In one receiver, for example, a three-position switch is used to produce a total i-f band pass of 10 kc, 6 kc, and 3 kc. Crystal filters often are incorporated in receivers used for extremely selective c-w signal reception.

139. Gain of I-F Stage

a. The gain attained in each i-f stage depends on the required *relative bandwidth* for a given i-f carrier frequency, the value of the intermediate frequency, and the transconductance, g_m, of the tube. The gain of the stage is *inversely proportional* to the relative bandwidth. In other words, the greater the ratio of the required bandwidth to the resonant frequency (i-f carrier), the smaller is the possible gain. I-f transformers of a given Q and coupling coefficient k have the same relative bandwith regardless of the frequency of operation (i-f).

b. The gain decreases as the frequency of the i-f carrier increases because of losses in the circuit and tube. High-frequency losses are caused chiefly to *loading* of the input circuit, which results from a lowering of the input impedance of the tube. The input impedance decreases at higher frequencies, because the tube interelectrode capacitances offer less reactance at these frequencies. The effect is to offer a resistive and capacitive shunt to the incoming signal. At very high frequencies, loading also is caused by the *transit time* of the electrons from the cathode to the plate (par. 49*d*(2)).

c. Finally, the gain of an i-f stage is directly proportional to the transconductance of the tube used. Modern pentodes have high values of transconductance. The *over-all gain* of the i-f amplifier is the *product* of the individual gains of each stage. If two identical i-f stages are used, the total gain is simply the *square* of the gain of one stage; for three identical stages, it is the cube, and so on.

140. Selection of Intermediate Frequency

a. The selection of the intermediate frequency is a compromise between various conflicting factors. The higher the intermediate frequency, the lower is the selectivity and the gain of the stage. On the other hand, it is impractical for the intermediate frequency to be greatly lower than the signal frequency. This is because trouble results from *image interference* if the *difference* between the signal frequency and the i-f is made very great (par. 149). A low i-f also increases the undesirable interaction between the signal and oscillator frequencies; pulling of the oscillator frequency by the mixer has been discussed previously. Although the selectivity and gain for low intermediate frequencies are excellent, image interference and pulling must be taken into account.

b. The selection of the i-f is a careful compromise between the desired selectivity and gain, and the permissible image interference and amount of pulling. For a-m reception up to approximately 10 mc, intermediate frequencies from 455 to 465 kc have been found satisfactory. An i-f of 455 to 456 kc generally is used for a-m communication receivers.

141. Improving Receiver Selectivity

It usually is desired to increase the selectivity of a superheterodyne receiver in order to reduce interference resulting from signals adjacent to the desired signal frequency, to cut down noise, and to eliminate *audio images* (explained below). The selectivity of superheterodyne receivers can be increased substantially by narrowing the bandwidth of the tuned i-f circuits. The limit of selectivity that can be used for voice reception is a bandwidth of approximately 2,000 cps. For c-w reception, the bandwidth can be as narrow as 50 to 100 cps. Such extreme selectivity, however, requires exceptional frequency stability at both the transmitter and the receiver, and makes it difficult to tune in a desired signal. The slightest frequency instability causes the signal to drift out of the restricted bandpass of the receiver.

a. Regeneration. Highly selective reception is extremely difficult to obtain with an ordinary i-f amplifier unless the chosen i-f is very low, which is rarely possible, or unless an impractically large number of tuned circuits is used. Fortunately, other methods exist for attaining the necessary degree of selectivity. One commonly used method is to introduce regeneration into one of the i-f amplifier tubes by providing a small amount of capacitive coupling between the grid and the plate. Sufficient regeneration usually is obtained by placing a short length of wire, one end of which is connected to the grid of the i-f tube, in the vicinity of the plate lead. The amount of feedback can be controlled by the ordinary cathode-resistor gain control, if provided. When the resonance curve of the plate tank circuit is peaked, regeneration has a pronounced effect. The selectivity of the i-f stage at critical regeneration (just below oscillation) is extremely sharp. The increased selectivity of regeneration also reduces the response to noise permitted to pass the preceding stages of the receiver, improving the signal-to-noise ratio. The disadvantage of regeneration, however, is the fact that it is never quite stable. The selectivity of the receiver is apt to vary considerably at times, and the gain is reduced for strong input signals.

b. Crystal Filters.

(1) As previously explained, a *piezoelectric quartz crystal* acts like a tuned circuit with an extremely high Q, and, correspondingly, high selectivity. A quartz crystal, therefore, can be used to advantage as a selective filter between two conventional i-f tuned circuits. The thickness of the crystal for this purpose is of the required value for resonance at the desired intermediate frequency.

(2) Two crystal filter circuits are shown in figure 188. In each, the crystal is made part of a balance bridge circuit, consisting of symmetrically fed input and output i-f circuits, the crystal, and a crystal *phasing capacitor*, *C*2. In A, the secondary of the input i-f transformer, *L*2, is balanced to ground through a pair of capacitors, *C*3 and *C*4; in B the same purpose is achieved through the center-tapped secondary winding, *L*2, of the mixer output transformer. The crystal filter impedance must be matched correctly to the input circuit of the following stage, which is the first i-f amplifier. This is accomplished in A by feeding the output of the filter circuit through an adjustable coupling capacitor, *C*5, to a tap on the input coil, *L*3, of the next stage. In B, the same result is obtained by replacing the tap with the primary *L*3 of an impedance-matching transformer. By closing switch *S* across the crystal, the filter is shorted out, and an ordinary i-f stage remains.

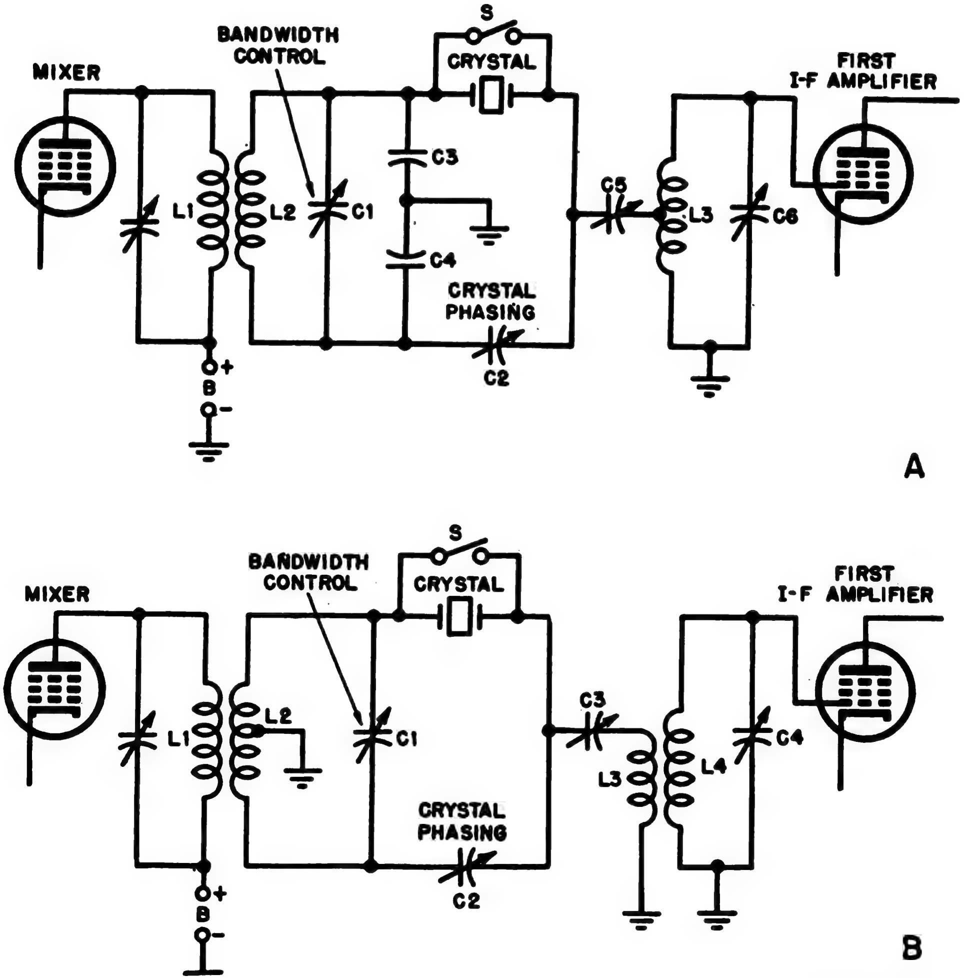


Figure 188. Crystal filter circuits.

(3) To understand the need for the phasing capacitor, $C2$, the equivalent circuit of the quartz crystal (fig. 56) is considered. The crystal itself is represented by a series R-L-C circuit, which is shunted by the parallel capacitance of the crystal holder, with the crystal as the dielectric. At a certain frequency, the R-L-C circuit representing the crystal goes into series resonance; at a slightly higher frequency, the combination of crystal and holder becomes parallel resonant. The bridge circuit (fig. 188) with capacitor $C2$ permits neutralizing the electrostatic capacitance of the crystal and holder so that only the high-Q series-resonant circuit exists. In this way, the crystal filter passes the desired signal at the series-resonant frequency of the crystal but greatly attenuates all other frequencies. If the electrostatic holder capacitance is not balanced out by $C2$, it can bypass some undesired signals around the crystal.

(4) The phasing capacitor, $C2$, has another important use in addition to minimizing the crystal holder capacitance. If the holder capacitance is not completely neutralized, a desirable parallel resonance occurs, the frequency of which can be adjusted by $C2$. At the frequency of parallel resonance, the filter has maximum signal rejection in contrast to the maximum signal response at the series-resonant frequency. Consequently, interfering signals that are close to the desired signal (within 1,000 to 2,000 cps) are rejected effectively by adjusting $C2$, so that the parallel resonant frequency coincides with the interfering frequency.

(5) The bandwidth of the crystal filter is largely controlled by the effective resistance of the input circuit that excites the crystal. This resistance is in series with the crystal, and so lowers its Q. As the effective Q of the crystal decreases, the selectivity is decreased, or, equivalently, the bandwidth is increased. Consequently, when the input-tuned circuit, $L2C1$ (fig. 188), is adjusted to parallel resonance at the crystal frequency, the effective resistance which the crystal sees is high, and consequently the bandwidth is maximum. When the input circuit is detuned, however, by varying the tuning capacitor, $C1$, the resistance in series with the crystal is low and the bandwidth becomes small. The bandwidth of the crystal filter can be controlled in this manner by adjusting capacitor $C1$. In practice, this is generally done by a multiple switch, which permits selecting different fixed capacitors with predetermined bandwidth characteristics. Other circuits have switching arrangements for changing the resistance in the circuit.

c. Audio Filters. In addition to the highly effective crystal filters, sharply tuned filters sometimes are inserted into the *audio* stages of the receiver. These may consist of simple resonant circuits inserted into the plate-coupling circuit of an a-f amplifier tube, or they can be more elaborate band-pass filters. In either case, their purpose is to pass a very narrow audio band containing the desired signal, but eliminating all undesired frequencies outside of this passband.

142. Detector Stage

a. Diode Detector.

(1) Most superheterodyne receivers utilize a diode detector for rectification of the modulated signal. Because of the linear characteristic between the modulated r-f input voltage and the rectified output current, a diode is capable of handling high-level signals with little distortion. It is, therefore, well adapted for use after the high-gain i-f stages of a superheterodyne receiver, where the more sensitive grid-leak detector and the plate detectors would be overloaded. Therefore, diode detectors are preferred over other detectors in superheterodyne receivers.

(2) The diode detector has no gain, however, so that there is a loss of signal strength. To make up for this loss, the diode detector rarely is used alone, but is combined with an audio amplifier in the same stage. As will be seen later on, the use of dual-function tubes (diode-triodes and diode-pentodes) makes this a comparatively simple matter. The gain of the combined detector-amplifier stage is then comparable to that provided by other types of detectors.

(3) More serious is the comparatively large current the diode detector draws from its tuned input circuit. This current damps out the resonant peak of the tuned circuit, substantially reducing the selectivity of the stage. This loss in selectivity must be compensated for by having a sufficient number of tuned stages in the receiver to make the over-all selectivity satisfactory. In receivers with a separate tuned r-f amplifier and two i-f stages the selectivity is sufficient.

b. Circuit and Operation.

(1) In practice, two types of diodes are in use—*crystal* diodes and vacuum-tube diodes. Crystal diodes can be *galena*, *silicon*, or *germanium* types. At very high frequencies, crystal diodes, especially of the germanium type, often are preferred to vacuum-tube diodes. A crystal may be compared to an imperfect form of diode, since it permits current to flow freely in one direction, but does not completely suppress it in the opposite direction. In a crystal diode, a small current *can* flow in the reverse direction. In contrast, vacuum-tube diodes permit current flow in only one direction, suppressing it completely in the opposite direction (when the plate is negative). Apart from this, the principle of detection in a crystal diode is similar to that in a vacuum-tube diode. The following analysis is based on the operation of the common vacuum-tube diode detector.

(2) The basic circuit of a vacuum-tube diode detector is shown in A of figure 189. It consists of a signal input circuit, which is the secondary of the last i-f transformer, a diode rectifier tube, and an *R-C* filter. The action of the circuit can be considered as that of a half-wave rectifier. The i-f signal is coupled to the plate of the diode through the i-f input transformer. The tube conducts only when the plate is positive in respect to the cathode. Consequently, whenever the signal voltage at the plate is positive, a current pulse flows through the tube and the load resistance, *R*. During the negative half-cycles of signal voltage, no current flows. The output of the tube, therefore, consists of a series of rectified i-f current pulses.

(3) The magnitude of the current pulses depends on the signal voltage at the plate. The plate-current plate-voltage characteristic of a typical diode is shown in B. For plate voltages sufficiently large to operate the tube beyond the curved lower bend, the characteristic is almost perfectly linear. The magnitude of the rectified plate-current pulses thus will be nearly proportional to the signal voltage on the plate, and so will reproduce the modulation of the signal voltage. The remaining i-f carrier variations are smoothed out by filter capacitor *C*. The value of this capacitor must be sufficiently large that it has a very low reactance to i-f variations, but a relatively high reactance to audio frequencies. In other words, it should provide minimum opposition to high frequencies and maximum opposition to audio frequencies. For this condition, the capacitor bypasses the i-f variations around *R*, and the a-f currents develop a voltage across *R*.

(4) The action of capacitor *C* requires more detailed consideration. Each positive i-f current pulse through the diode develops a voltage across capacitor *C*, and consequently across load resistor *R*, connected in parallel with it. The capacitor charges up to the *peak value* of each voltage pulse. Between successive peaks, the applied signal voltage drops to zero and becomes negative, thus cutting off the plate current during these intervals. Since the capacitor tends to hold its charge, the voltage across *R* and *C* does not fall to zero. As the capacitor slowly leaks off its charge through the resistance during the intervals of plate-current cut-off, the voltage across the *R-C* combination also drops slowly. With the next plate-current pulse, the charge on the capacitor again is replenished, and the voltage across the *R-C* load rises to the new peak value of this plate-current pulse. Thus, the voltage across the capacitor always rises to the peak value of the plate-current pulse and drops off slowly between current pulses. In this way, the load voltage

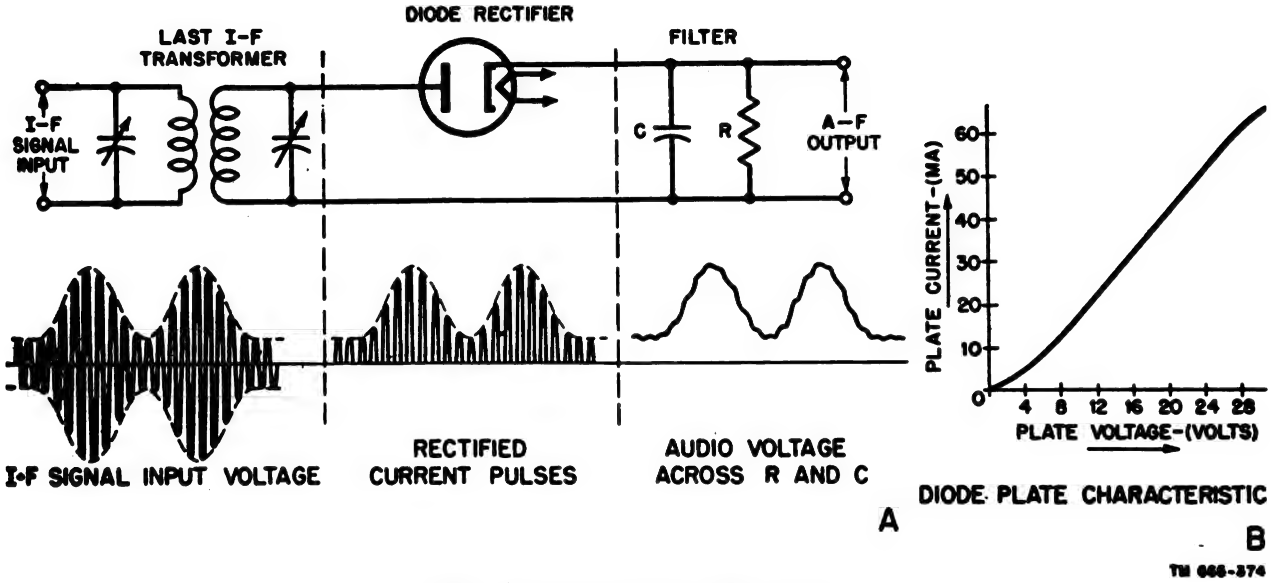


Figure 189. Action of basic diode detector.

across *C* follows the peak values of the applied signal voltage, and so reproduces the a-f modulation shown by the waveform at the right in A of figure 189. The curve is somewhat jagged, since the voltage across the capacitor does not follow the modulation peaks perfectly, but drops off slightly between successive peaks. The jaggedness represents a small i-f ripple in the load voltage, which is generally negligible for a properly chosen resistance-capacitance combination.

(5) In figure 190, which represents a diode detector and triode amplifier combined in the same stage, the signal input is coupled through the *i-f* transformer to the diode plate. The rectified signal appears across load resistance *R* in the cathode circuit of the tube and is smoothed out by capacitor *C*. The reactance of *C* must be small compared to the resistance of *R* at the *i-f* frequency being rectified, but it should be relatively large at audio frequencies. The triode grid is connected directly to a tap on the diode load resistor. The average rectified cathode current supplies a d-c voltage at the tap, which provides bias for the triode grid. With a modulated signal present, the *a-f* variations are superimposed on the d-c and are transferred from the load resistance to the triode grid,

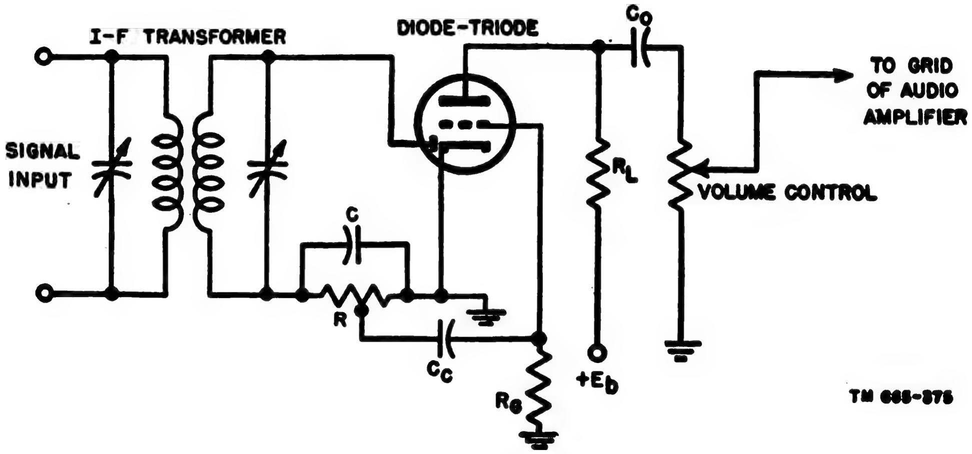


Figure 190. Diode detector circuit.

where they are amplified. The amplified audio voltage appears across the plate-load resistance R_L, and is coupled through C_o and the volume control to the grid of the next stage. The volume control permits tapping the audio output voltage at the desired level. Instead of resistance-coupling, transformer coupling can be used, and a diode-pentode can be substituted for the diode-triode tube. If a pentode is used, resistance coupling generally is preferable.

143. Automatic Volume Control

a. Need for AVC. Although manual volume controls permit regulating the gain of a receiver to a convenient output level, for several reasons it is desirable to have additional automatic control of the receiver gain. One reason is that it prevents extreme variations in loudspeaker volume. When a receiver is tuned from a weak station (for which the volume has been turned up), to a strong station, the loudspeaker will blast unpleasantly. The variations in signal strength of a signal carrier because of fading and other conditions also result in wide fluctuations of the loudspeaker volume. Furthermore, variations in signal strength at the antenna, if not compensated for, can cause serious trouble by overloading the *r-f*, *i-f*, or detector stage of the receiver, which in turn results in distortion of the signal. An automatic-volume-control circuit overcomes these troubles by automatically regulating the gain of the *r-f* and *i-f* stages. By making the gain of these stages less for a strong signal than for a weak signal, approximately constant signal input can be maintained at the detector regardless of signal strength at the antenna. The output volume from the speaker then will depend only on the degree of modulation at the transmitter.

b. Circuit and Operation.

(1) The *r-f*, *i-f*, and mixer stages of a receiver utilize remote cut-off tubes whose gain can be controlled by varying the grid bias. By making the grid bias of these tubes more negative, the stage gain is reduced. If the gain of several stages is controlled by a negative bias voltage, the value of which depends on signal strength (*avc* voltage), ample reduction in receiver sensitivity can be attained for strong signals. The gain of the receiver, however, never can be *increased* beyond its maximum value in the absence of avc. The *avc* circuit simply provides this negative bias voltage, whose magnitude is proportional to signal strength, for *reducing* receiver gain.

(2) Figure 191 shows the addition of an avc circuit to the ordinary diode detector just discussed. The operation of the diode-detector portion is identical to that described in paragraph 142*b* and illustrated in A of figure 189. When the diode current flows through the load resistance, R, it generates a voltage drop which makes the left end of R negative in respect to ground. This negative voltage drop is applied through filter circuit $R1C1$ to bias the grids of the preceding stages which are to be controlled. When the signal strength increases, the bias

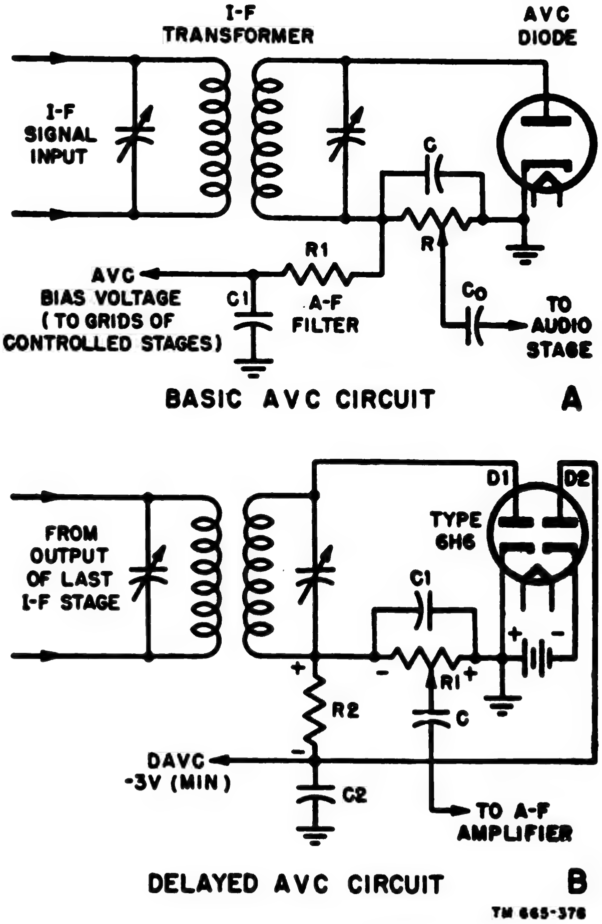


Figure 191. Automatic volume control circuits.

voltage developed across R also increases because of the greater average rectified diode current; therefore, the gain of the controlled stages is reduced. As a result, the output of the last *i-f* stage to the detector is increased only slightly for a large increase in signal level. For a decrease in signal level from the previously steady value, the action is reversed. The *avc* bias decreases, and the gain of the amplifier stages and the detector increases. The *avc* circuit always tends to counteract changes in signal level at the antenna of the receiver.

(3) The filter circuit, $R1C1$, prevents the *avc* bias from varying at an audio-frequency rate. Load resistance R and capacitor C of the detector are designed to filter out *i-f and r-f* variations, so that the voltage across them varies only at the audio-frequency rate of the modulation. If the *avc* were taken directly from R without filter $R1C1$, the individual *a-f* variations of the avc voltage would vary the receiver gain, thus tending to counteract the modulation of the carrier, and so produce distortion. Filter $R1C1$ is designed to prevent this from happening by smoothing out the *a-f* variations in the *avc* voltage, so that it does not follow the modulation and is substantially constant. The *avc* voltage, therefore, cannot vary as fast as the audio-range frequencies, but acts nevertheless sufficiently rapid to compensate for the slower amplitude variations caused by signal fading and changes in tuning from one station to another.

c. Delayed Automatic Volume Control.

(1) In the circuit shown in A of figure 191, a certain amount of *avc* bias is developed even for weak signal inputs. In many applications, however, it is desirable to have maximum r-f and i-f gain available for weak signals. Some communication receivers permit switching off the *avc* with a manual cut-out switch, when it is desired to have maximum sensitivity available. This can be achieved automatically by means of a so-called *davc* (*delayed avc*) circuit, which prevents the application of *avc* bias until the signal strength exceeds a certain predetermined value.

(2) In B, the diode section, $D1$, of the twin diode acts as a detector and *avc* diode. $R1$ and $C1$ are the diode load resistance and filter capacitor, respectively, while $R2$ and $C2$ act as an *avc* filter to smooth out the audio variations so that the avc bias will be relatively constant for these frequencies. The audio output from the detector is taken from a tap on load resistance $R1$ and is coupled through C to the grid of the first audio amplifier stage. The cathode of diode section $D2$ is returned through a fixed supply voltage of -3 volts to the cathode of $D1$, and ground. This fixed voltage can be supplied by a small bias cell, or by connecting the cathode of $D2$ to a tap on a power supply voltage divider. Because of the presence of the fixed voltage, a direct current flows through $R1$ and $R2$ in series with diode $D2$. The voltage drop caused by this current places the *avc* tap at the lower end of $R2$ at approximately -3 volts, since the voltage drop across $D2$ is negligibly small. The 3-volt fixed bias is approximately the proper minimum value for maximum sensitivity of the remote cut-off tubes.

(3) For signals that are not strong enough to develop a rectified voltage across $R1$ in excess of 3 volts, the *avc* bias to the controlled tubes remains constant at -3 volts. For strong signals, however, the average value of the rectified signal voltage across $R1$ exceeds 3 volts, and thus cancels out the fixed 3-volt bias. Consequently, for signals exceeding 3 volts, the plate voltage at $D2$ becomes negative in respect to the cathode, and current stops flowing through $D2$. The *avc* voltage then is controlled solely by the rectified signal voltage developed across $R1$. Any further increase of the rectified signal voltage beyond 3 volts then progressively increases the *avc* bias to the controlled stages, and so reduces their gain. Other *davc* circuits than the one described are frequently used, but the above illustrates the basic principles. Duplex-diode triodes and duplex-diode pentodes can be

utilized to advantage to combine the functions of detection, *davc*, and audio amplification in one stage.

d. Quiet AVC.

(1) One disadvantage of *avc* is that it adjusts the receiver for maximum sensitivity when no signal is received. Hence, while tuning the receiver, the background noise between stations is often excessive. Automatic circuits have been developed for avoiding this condition by *muting* the receiver during tuning between stations. The most frequently used muting systems, known as *squelch* or *qavc* (*quiet avc*) circuits, utilize the *avc* bias to block the audio or detector stage, making the receiver silent during tuning.

(2) One arrangement utilizes the principles discussed above for securing a delayed *avc* voltage. The detector diode of a twin-diode tube, however, is negatively biased with a constant delay voltage. The detector section, therefore, normally is cut off by the negative plate voltage until a signal of preset intensity overcomes the diode bias voltage and allows the detector to function normally.

(3) Another popular circuit normally blocks the first audio amplifier tube and permits it to function only when a signal is received that is stronger than the noise. An ordinary diode detector and *avc* circuit are utilized in conjunction with a special control or *squelch* tube. The output of the detector is coupled to the grid of the first audio amplifier tube, which utilizes a cathode resistor to provide its *normal* bias. The control tube is an ordinary triode or pentode whose grid bias is controlled solely by the *avc* voltage. The plate current of this control tube is made to flow through a portion of the grid resistance of the first audio amplifier and develops a large negative bias voltage there. In the absence of a signal, no *avc* bias is applied to the control tube, and the plate current of the control tube will develop sufficient grid bias in the grid resistor of the audio amplifier tube to drive the tube to plate-current cut-off. Without an incoming signal, therefore, the audio amplifier is blocked. When a signal of sufficient strength is received, however, the *avc* bias applied to the grid of the control tube will drive it to cut-off, and plate current stops flowing. Without control-tube plate current, no additional grid bias (blocking voltage) will be developed in the grid resistance of the grid audio amplifier. The tube, therefore, will unblock and function normally. This system discriminates against all signals not sufficiently strong to cut off the control tube and so permit the first audio amplifier to operate normally.

144. Noise Discrimination

a. Types of Noise. Highly sensitive modern superheterodyne receivers always have some inherent background noise which appears in the output as hiss and crackles. Some noise arises in the tubes and circuits of the receiver itself because of shot effect, thermal agitation, and other random sounds. Most of this receiver noise comes from the input circuit of the first stage, and is amplified by each succeeding stage. This amplified noise masks noise generated in other stages. Lightning and man-made interference such as electrical appliances and automobile and aircraft ignition systems cause noise in receivers which usually appears as hiss. This can result from commutator sparking of electric motors. Spark and arc discharges, such as ignition sparks, switches, and power leaks, usually result in shot noises, consisting of pulses of very short duration but having amplitudes considerably higher than those of the desired signals themselves. It is this characteristic of impulse noises that makes it possible to devise circuits that can discriminate more against the noise pulses than against the desired signal.

b. Noise-Suppression Circuits.

(1) Two general methods have been successful in reducing impulse noise. One is to render the receiver inoperative during the brief duration of any pulse which appreciably exceeds the signal amplitude. Circuits for accomplishing this are known as *silencers*, or *squelch circuits*. They are similar in design and function to *qavo* (quiet automatic volume control) circuits. The other method of reducing impulse noise is to limit the operation of

the receiver to the maximum amplitude of any desired signal. Although the receiver output is not cut off, pulse amplitudes which are greater than the desired signal amplitude cannot be reproduced in the output. Circuits that accomplish this operation are called *limiters*. Since limiters reproduce the portion of the noise pulse that is less than the maximum desired signal amplitude, their effectiveness increases directly with the amplitude of the noise impulses. For noise pulses of very high amplitude, the improvement in signal-to-noise ratio is considerable.

(2) *Noise-silencing*, circuits usually are designed to bias the final i-f amplifier tube to plate-current cut-off for the duration of a noise pulse, thus silencing the receiver. In these circuits, noise voltages in excess of the maximum desired i-f signal voltage are taken off the control grid of the i-f amplifier tube. The noise voltage then is amplified by a pentode stage and is fed to a full-wave rectifier. The resulting d-c pulse output voltage is applied as an instantaneous negative bias to the same i-f amplifier tube. It reduces the gain or completely cuts off the tube, depending on the amplitude of the pulse. A variable resistance delay circuit, called *threshold control*, is incorporated in the rectifier so that rectification does not start until the noise voltage exceeds the maximum desired signal amplitude. The delay is obtained in the same way as in a delayed *avc* circuit.

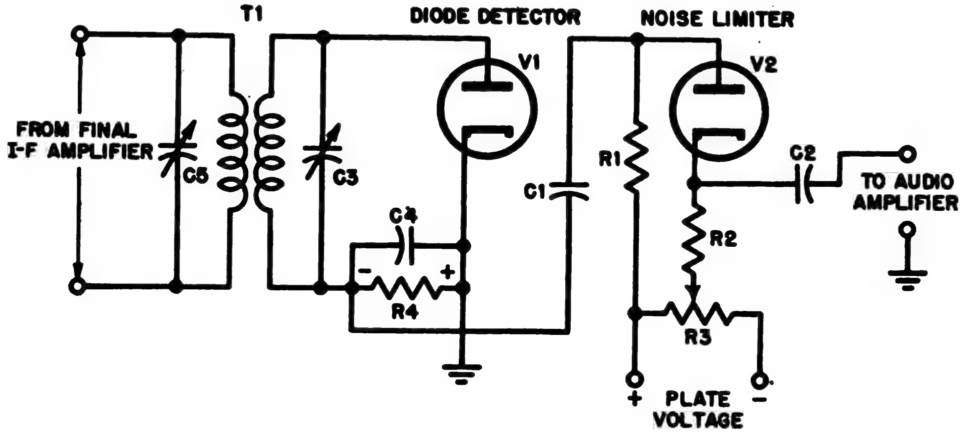


Figure 192. Typical audio noise limiter.

(3) Noise reduction also can be accomplished effectively by limiting the amplitude of the audio voltage that is applied to the a-f amplifier of the receiver. Such limiters are of simple design and keep the desired signal output nearly constant. However, this type of limiter cannot prevent large noise voltages from overloading the stages of the receiver ahead of the limiter. A typical noise limiter connected to a diode detector of a superheterodyne receiver is shown in figure 192. Diode *V*1 and its associated circuit act as an ordinary detector following the final i-f amplifier. Diode *V*2 operates as a valve through which the audio output of the detector must pass to the grid of the a-f amplifier tube.

(4) The steady diode current of *V*2 resulting from the positive plate voltage is modulated by the audio signal coming from the detector. As long as the plate of *V*2 is positive in respect to its cathode, conduction continues. Conduction ceases as soon as an audio noise voltage of sufficiently large magnitude swings the plate negative in respect to the cathode. The diode-current cut-off point is selected by the adjustment of *R*3. It is set so that the maximum desired audio signal just passes through *V*2. Noise pulses higher in amplitude than this maximum signal then are cut off. Fairly high audio signal voltages are required for good limiting action. The limiter can be used for both c-w and a-m signals.

145. Audio Amplification

a. Function of Stage. After the modulation has been extracted from an incoming signal, a relatively weak audio voltage is made available at the output of the detector. In practically all cases, this audio signal first must be strengthened by one or two stages of audio amplification before it is capable of energizing a pair of headphones or a loudspeaker. It is the function of the audio amplifier to raise the audio voltage from the detector to a comfortable listening level with a minimum of distortion. The amount of audio amplification needed depends on the power requirements of the reproducer. One stage of audio amplification generally is sufficient to operate a headset or a small loudspeaker. A large loudspeaker, however, requires a powerful audio amplifier consisting of several stages.

b. Voltage and Power Amplifiers.

(1) The audio amplifier must develop sufficient *power* to operate the reproducer properly. If the power requirements are large, several stages must be used. The last or *final stage* of the audio amplifier is designed to provide this needed power, and is therefore called the *power output stage.* By choosing triode, pentode, or beam power tubes with a high transconductance (g_m) for this stage, large plate currents can be made available with sufficient *grid excitation* (input voltage) to the tube.

(2) The power output stage must have sufficient grid excitation voltage that the full rated plate current is produced when the audio signal voltage at the input swings to its positive peak. In other words, the plate current of the power tube must reach its rated value for the maximum audio signal normally to be expected at the grid of the tube. To provide this value of grid excitation, one or more stages of *voltage amplification* are required. In a voltage amplifier the voltage gain of the stage is the primary objective, and the plate current or power output of the tube is of no interest. For this reason, high-u tubes, capable of providing large output voltages, are chosen as voltage amplifiers. Pentodes, which provide very high voltage gain, generally are preferred to triodes.

(3) If the reproducer requires little power, the detector stage often is combined with the first audio amplifier, which in turn is coupled to the power output stage.

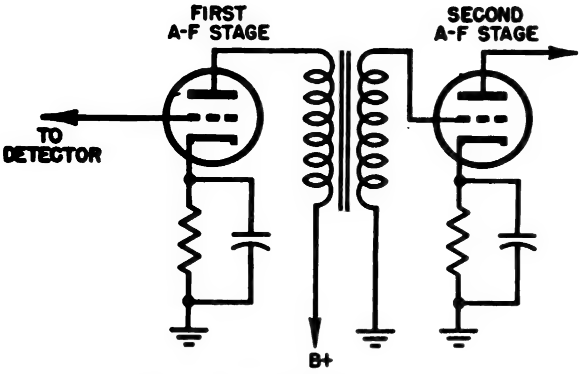
146. Coupling

Three methods generally are used to couple the amplifier audio signal from the plate of one amplifier stage to the grid of the succeeding stage (fig. 193). These are transformer coupling, illustrated in A, resistance coupling, in B, and impedance coupling, C. The grid of the first a-f stage is connected to the detector output. Depending on power and gain requirements, the second a-f stage can be either another voltage amplifier similar to the first, or it may be the power output stage that energizes the reproducer.

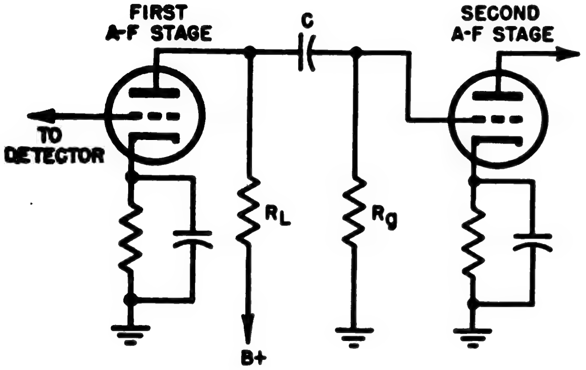
a. Transformer Coupling.

(1) The audio signal from the detector, shown in A, is impressed on the grid of the first amplifier tube, where it is amplified. The a-c component of the plate current develops a voltage across the primary of the interstage transformer, which in turn induces a voltage in the secondary. This voltage is applied to the grid of the second audio amplifier stage, where it is further amplified. Bias for each amplifier tube is supplied by a cathode resistor, which is bypassed for audio frequencies by a shunt capacitor.

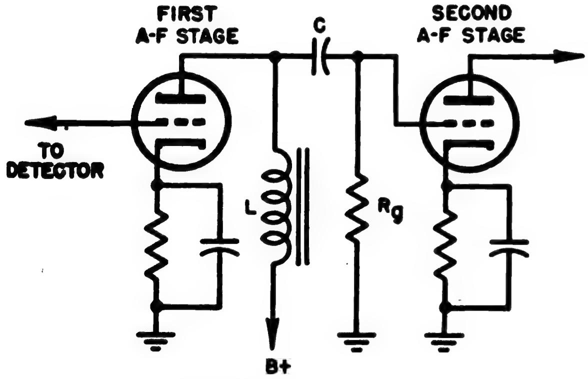
(2) The chief advantage of transformer coupling is that additional voltage amplification can be obtained by using a transformer with a step-up ratio between the primary and the secondary. Thus, if the voltage gain of the first a-f amplifier is 20, and the transformer has 1 to 3 step-up ratio, the total voltage gain from the grid of the first a-f stage to the grid of the second a-f stage is 3 times 20, or 60. The additional voltage step-up provided by the transformer was of some importance in the early days of radio, when only low-mu triodes were available. With the development of high-mu triodes and pentodes, this advantage became less of a factor.



TRANSFORMER COUPLING A



RESISTANCE COUPLING B



IMPEDANCE COUPLING C

TM 665-377

Figure 193. Audio interstage coupling methods.

(3) Disadvantages of transformer coupling are the bulkiness and high cost of properly designed interstage transformers. It is a fairly difficult matter to design a transformer that will pass all the frequencies of the audio range uniformly and meet low distortion requirements. Most transformers tend to accentuate a frequency band between about 3,000 and 4,000 cps. This is caused by resonance resulting from the transformer self-inductance and the distributed capacitance of the windings. Self-resonance also produces considerable harmonic distortion. Unless specially compensated, the frequency response of the transformer falls off rapidly at low frequencies, and also falls off at frequencies above the resonant peak.

b. Resistance Coupling.

(1) A coupling network consisting of a plate-load resistor R_L, a coupling capacitor C, and a grid resistor R_g, shown in B, is used to transfer the signal from the plate of the first a-f stage to the grid of the second a-f stage. As before, cathode bias is utilized. Because the coupling network adds no gain to the amplifier, high-gain pentodes generally are preferred to triodes (shown here to simplify the discussion) when resistance coupling is used.

(2) The amplification of the resistance-coupled amplifier can easily be made uniform over the entire audio-frequency range. However, extreme uniformity in frequency response must generally be paid for by some reduction in the gain available from the stage. The voltage amplification of the first a-f stage increases directly with the value of the plate-load resistance, R_L, up to an upper limit given by the numerical value of the amplification factor of the tube. If R_L is made too high, however, the available plate voltage at the tube becomes low, and the output voltage is reduced. The response at high frequencies also drops off somewhat as R_L is increased. Since grid resistor R_g is effectively in parallel with R_L, its value must be high to avoid excessive shunting, thus reducing the output voltage. R_g must not be too high, however, since otherwise the gas currents of the tube will set up a considerable *positive* bias, which can harm the tube. In practice, R_g usually is made from one

to two times the value of R_L. Coupling capacitor C blocks direct current at the plate of the first a-f tube from reaching grid of the second stage. Its reactance must be negligible at the lowest frequency that is to be amplified. Under this condition, the response at higher audio frequencies will not be affected. Recommended values for the coupling network, cathode bias resistor, and capacitor are given in tube manuals for various operating conditions and tube types.

(3) Resistance coupling is used almost universally for audio voltage amplifiers, since its performance is excellent, and it is inexpensive, compared with transformer coupling. Where negligible amounts of power are involved (that is, voltage amplification), resistance coupling has no disadvantages.

c. Impedance Coupling. The impedance-coupled audio amplifier shown in C can be considered a resistance-coupled amplifier in which inductance L has been substituted for plate-load resistance R_L. The inductor lowers the d-c voltage drop occurring in R_L, but maintains a high impedance at audio frequencies. In this way, a higher plate voltage is supplied to the first amplifier tube for the same available d-c supply voltage. Consequently, the voltage output of the first a-f tube is higher than for resistance coupling. Impedance coupling is used rarely, since it does not provide the voltage step-up of transformer coupling, and has the same disadvantages.

d. Output Coupling. Figure 194 shows a typical pentode power output stage. High-gm pentodes or beam-power tubes are preferred to triodes in this application, since they provide relatively high output power with a small grid excitation voltage. The input of the power stage can be resistance-coupled as shown, for transformer-coupled to the output of the preceding voltage amplifier stages. To attain optimum power transfer from the high-impedance output tube to the low-impedance voice coil of the speaker, the output of the power stage is always transformer-coupled to the speaker. (Impedance matching of the output stage is discussed in detail in paragraph 151.) A screen-dropping resistor, R_s, and bypass capacitor C_s are used. If screen grid and plate both can be operated at the same voltage, R_s and C_s are omitted. Cathode bias is shown in the diagram, although fixed bias occasionally is utilized in power output stages.

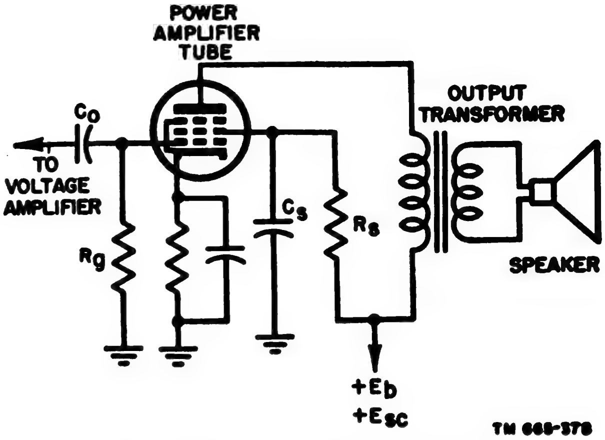


Figure 194. Output stage coupling.

147. Distortion

a. Frequency Distortion. If the audio amplifier does not pass uniformly all of the frequencies contained in the audio range (about 16 to 16,000 cps), it is said to have frequency distortion. For communication purposes, however, the primary objective is *intelligibility* rather than maximum fidelity. Good intelligibility is realized if the audio circuit amplifies frequencies from about 150 to 3,500 cps equally well. Frequency discrimination should be a minimum within at least this narrow band.

b. Harmonic Distortion. More serious is *harmonic distortion* produced by nonlinear circuit conditions. It will be remembered that vacuum tubes have characteristics that are not linear, especially at low plate currents and voltages. If the tube is operated in this curved portion of its i_p–e_g characteristic, the output current will not be proportional to the input voltage, and nonlinear distortion results. The output waveform then is no longer the same as the input waveform and contains frequency components that were not present in the input. These new frequencies in the output waveform are related harmonically to the frequencies present in the input circuit; that is, the added output frequencies are integral multiples of the input frequencies. Usually the second harmonic predominates, but odd harmonics also can be present. Harmonics cause unpleasant sound reproduction at the loudspeaker and therefore must be kept to a minimum. The primary source of *intermodulation distortion* is the presence in the desired signal of two or more strong frequency components which may or may not be harmonically related. The intermodulation distortion products are the sum and difference frequencies between any two or more strong signal components and are produced by the nonlinear characteristics of amplifier tubes.

148. Negative Feedback

a. When a portion of the output voltage of an amplifier tube is fed back to the input of the same or a preceding tube in opposite phase to the applied signal, *degeneration* takes place. A circuit for providing degeneration is called an inverse or *negative feedback* circuit. When degeneration is introduced in the circuit, the voltage fed back is opposing the applied input voltage and therefore reduces its amplitude. Since the feedback voltage subtracts from the applied input signal, the gain of the stage is reduced. Two important advantages compensate for this reduction in amplification. Frequency and nonlinear distortion both are reduced considerably for stages included in the feedback circuit. Also, the stability of the amplifier is increased materially.

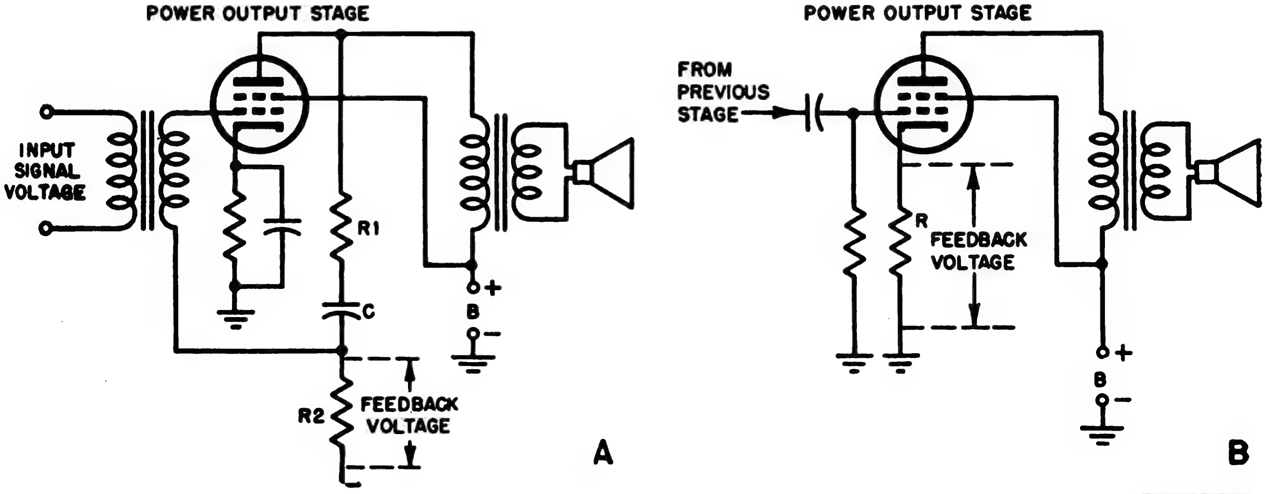


Figure 195. Negative feedback circuits.

b. Two commonly used circuits (fig. 195) illustrate the application of negative feedback in audio amplifiers. In A, a voltage divider consisting of *R*1 and *R*2 is connected across the plate circuit of an audio output tube. Capacitor C between the two resistors prevents the d-c plate voltage from reaching the grid of the tube. The voltage divider applies a portion of the output voltage of the tube back to the grid. This voltage is equal approximately to the fraction *R*2/*R*1 plus *R*2 of the output voltage. The feedback voltage is in series with the input transformer secondary and in opposite phase to the voltage induced in that winding by the preceding amplifier stage. This feedback is known as *constant-voltage* feedback, since its magnitude depends on the output voltage. It frequently is used to reduce distortion in output pentodes or beam-power tubes.

c. In B, negative feedback is obtained by omitting the bypass capacitor across the cathode bias resistor. As a result, the portion of the output signal voltage developed across cathode resistance *R* opposes the signal input voltage between the grid and ground. Consequently, degeneration takes place, and the gain of the stage is reduced. It can be shown that the plate resistance of the output tube is increased at the same time. This method of feedback is called *constant-current* feedback, since the feedback voltage is proportional to the cathode current.

d. These two simple circuits of figure 195 illustrate the basic types of negative feedback. Much more elaborate circuits frequently are used. For example, a portion of the output voltage from the secondary of the output transformer may be fed back over several stages to the grid of some preceding amplifier tube. In this way the over-all frequency response can be improved and the distortion reduced at the expense of voltage amplification. To compensate for this reduction in gain, an additional amplifier stage may be required.

149. Radio-Frequency Amplifiers

The basic superheterodyne receiver will operate without an r-f amplifier. However, one or two tuned r-f stages ahead of the frequency converter are used almost always in modern superheterodyne receivers, since several important advantages can be attained with an r-f amplifier. The most important of these are suppression of image interference, improvement in selectivity, improvement in signal-to-noise ratio, and isolation between the antenna and frequency converter (radiation suppression). The addition of the r-f amplifier, of course, also improves the gain of the receiver, but this is not its primary function since gain is more efficiently obtained in the i-f amplifier. The circuit and operation of an r-f stage in a superheterodyne receiver is the same as that of the r-f stage in a trf receiver (ch. 7).

a. Image Response.

(1) It has been explained that the mixer stage generates an intermediate frequency which is the frequency difference between two signals beating together. The two frequencies involved are the frequency of the incoming signal and the local-oscillator frequency. However, *any two signals* whose frequency differs by an amount equal to the i-f can produce an intermediate frequency in the mixer stage. Since the mixer output and the succeeding *i-f* stages all are tuned to the intermediate frequency, they cannot discriminate between different signals—desired or undesired—that produce this frequency.

(2) As an example, consider a superheterodyne receiver tuned to a desired incoming signal of 600 kc, with an intermediate frequency of 455 kc. Assume that the oscillator is tuned *above* the frequency of the desired received signal, which is usually the case. The oscillator therefore is set at a frequency of 600 plus 455 = 1,055 kc, so that the frequency difference is equal to the *i-f* (fig. 196). Assume also that an *undesired* signal is received with a frequency of 1,510 kc, and that this signal is present at the input of the mixer. The 1,510-kc signal, known as the *image frequency*, also beats with the oscillator frequency of 1,055 kc to produce an i-f of 455 kc. Since both the desired 600-kc signal and the undesired 1,510-kc image frequency produce the same *i-f*, *image interference* is caused in the *i-f* amplifier that cannot be suppressed by the *i-f* stage itself. Image suppression can be provided only by the tuned circuits of the mixer and the *r-f* amplifier stages preceding it by preventing the interfering signal from reaching the grid of the mixer.

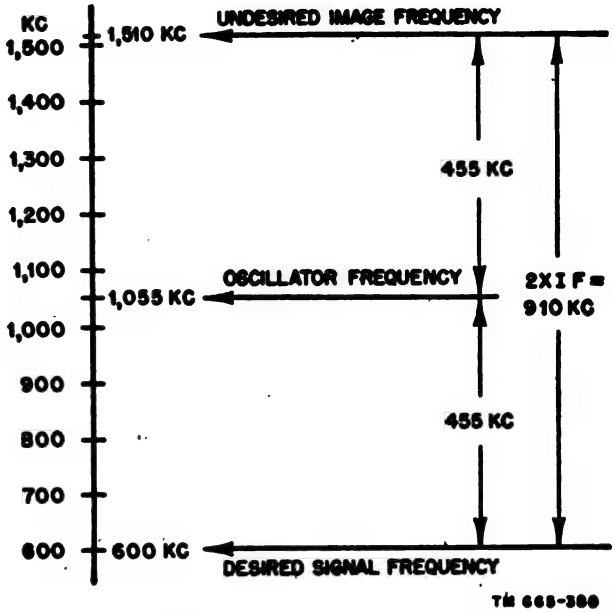


Figure 196. Image interference.

(3) The image frequency always differs from the desired signal frequency by an amount equal to *twice* the intermediate frequency. If the oscillator is tuned above the desired signal, the image frequency is the desired signal frequency plus twice the intermediate frequency. If the oscillator is tuned below the desired signal, the image frequency is the signal frequency minus twice the intermediate frequency. Consequently, the higher the image frequency compared to the signal frequency, the greater is the spacing between the desired signal and the image, and therefore the easier it is for the tuned circuits preceding the converter to suppress the response at the image frequency.

(4) For an *i-f* of 455 kc, the images of all but the lowest frequencies in the broadcast band (550 to 1,600 kc) fall outside the band. For those frequencies for which the image falls within the band (that is, signal frequencies below 1,600 minus 910=690 kc), the relative frequency separation between desired and image signal is so great that the image response of the tuned circuits is negligible. The same *i-f* of 455 kc in the short-wave band (6 to 30 mc), however, can cause bad image interference. For a signal of 20 mc, for example, the image frequency would be 20.91 mc (20 plus .910=20.91 mc), which is still a difference of 910 kc from the desired signal. The *relative* frequency spacing between desired and image signal is now only .91/20=.045, or 4.5 percent. It is clear that the tuned circuits of the r-f amplifier must be extremely selective to discriminate between signals separated by this small relative frequency difference. For application in the range from approximately 6 to 30 megacycles and also for very high frequencies, double conversion sometimes is used. For example, the incoming signal first may be converted to an intermediate frequency between 5 and 10 mc, and, after amplification, this frequency is *again* converted to a lower *i-f* of 445 kc. In this way, sufficient relative separation can be maintained between the signal and image frequencies. A receiver of this type is called a *double superheterodyne* receiver. Figure 197 shows a double conversion communication receiver.

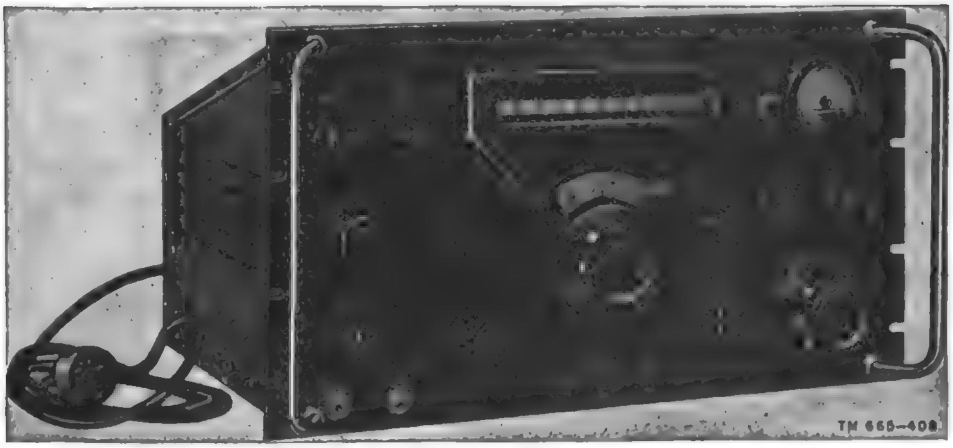


Figure 197. Communications receiver.

(5) If signal and image frequencies of equal strength are applied to the input of a receiver, the ratio of the signal voltage to the image voltage at the output of the receiver is called the *image rejection ratio*. As explained, the image rejection ratio increases with the intermediate frequency selected. For a *given* i-f, the image rejection ratio depends directly on the number and bandwidth of the tuned r-f circuits preceding the mixer tube. To obtain a sufficiently great image rejection ratio, some communication receivers operating at high frequencies utilize as many as three tuned r-f amplifier stages ahead of the mixer. In general, however, one of two tuned r-f stages are used.

(6) Besides images, other spurious signals can produce an intermediate frequency, and so cause interference. Harmonics of the local-oscillator frequency can beat with signals far removed from the desired frequency to produce an i-f output that can be heard. Heterodyning can occur also in the r-f amplifier itself, if sharp cut-off pentodes with nonlinear characteristics are used. Finally, harmonics generated by a nonlinear detector can be reintroduced in the r-f and mixer stages by stray coupling and cause interference by beating with the desired signals. Interference caused by beating the

desired signal and spurious frequencies is called *cross modulation.* To prevent this type of interference, high selectivity in the r-f stages, good isolation, and adequate shielding, especially of the local oscillator, are necessary.

(7) In addition to the spurious signals which can produce intermediate frequencies, there is cross-product interference—that is, sum and differences. For instance, if one listens to the frequency which is the sum or difference of two nearby stations, the two signals may be heard.

b. Signal-To-Noise Ratio. In addition to increasing the selectivity and image ratio of the receiver, a tuned r-f amplifier also improves the signal-to-noise ratio. The converter of a superheterodyne receiver has little gain and a fairly high amount of noise. If it is used directly after the antenna without an intermediate r-f amplifier, the converter contributes its noise to the signal, and amplifies it a little. Consequently, the signal-to-noise ratio is poor. The situation is reversed if an r-f amplifier is interposed between the antenna and the converter. The gain of the r-f amplifier is high, whereas its inherent noise is fairly low. Consequently, the initially weak signal is greatly amplified with little addition of noise, and the signal-to-noise ratio at the output of the r-f amplifier is high. Having reached this high level of amplification, the signal is little affected by the additional noise introduced by the converter stage.

c. Isolation. An r-f amplifier provides good isolation between the antenna and the converter stage. Changes in the load presented by the antenna for different frequencies cannot affect the mixer circuit, with an r-f amplifier interposed. Thus, less interaction takes place between the mixer and oscillator portions of the frequency converter. The isolation provided by the r-f amplifier also helps to keep the output of the local oscillator from reaching the antenna and being radiated. Finally, an r-f stage aids in preventing strong undesired signals at the antenna from reaching the mixer and detector stages, which can cause cross modulation, as described above.

d. Wave Traps.

(1) If strong signals in the intermediate-frequency range are present at the antenna of a receiver and reach the mixer, they will be amplified by the i-f amplifier and cause interference. *Wave traps* are simple parallel-resonant or series-resonant circuits (A and B of fig. 198) which eliminate signals in the i-f range, or other specific unwanted frequencies.

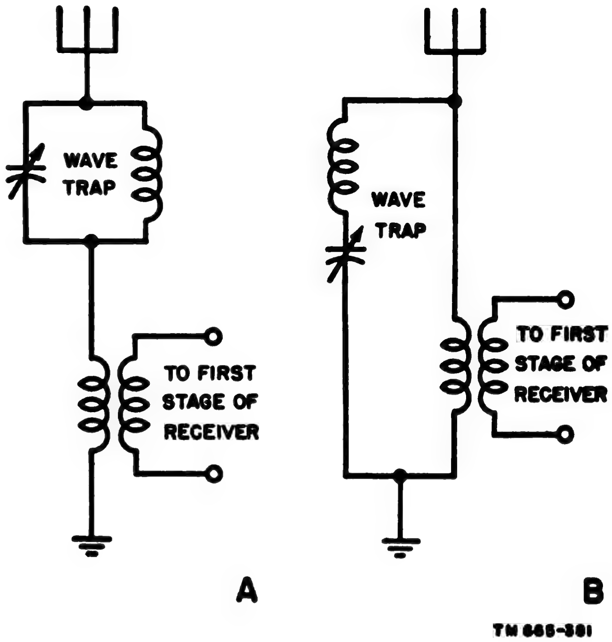


Figure 198. Wave-trap circuits.

(2) The parallel-resonant circuit in A is connected in series with the antenna and input transformer. It is tuned to the frequency of the i-f or other undesired signal. It will thus present to currents of this frequency a very high impedance, but permit currents of all other frequencies to enter the receiver.

(3) The series-resonant circuit in B is connected in parallel with the antenna input circuit. It is tuned to the frequency of the unwanted signal. It offers to currents of this frequency a very *low* impedance, and thus effectively bypasses these unwanted currents to ground. For currents of all other frequencies, however, the impedance of the wave trap is high compared to the antenna input circuit, and consequently little shunting results at these frequencies.

e. R-F Gain Control.

(1) The amplifier in the typical r-f stage, shown with both manual and automatic sensitivity control in figure 199, is of the

design used for trf receivers. The signal from the antenna or a preceding r-f stage is coupled by means of an r-f transformer to the tuned grid circuit of the amplifier tube. A remote cut-off pentode is used to provide the proper characteristic for smooth variation of gain with applied grid bias. The amplified output signal from the plate circuit is coupled through an r-f transformer to the tuned grid circuit of the following stage, which can be the mixer stage, or another r-f amplifier of similar design. The screen grid is supplied from the d-c voltage supply through the screen-dropping resistor, *R*2, which is bypassed for r-f by capacitor *C*2. Cathode bias is utilized.

(2) Both manual and automatic gain control are attained by varying the bias voltage present at the grid of the remote cut-off pentode. *Manual gain control* is secured in the cathode circuit by a variable resistor in series with a fixed resistor, *R*1. Both are bypassed for r-f by capacitor *C*1. *R*1 provides the necessary minimum bias to the grid of the tube when the manual gain control is set at zero resistance. By increasing the resistance of the gain control, more bias voltage is developed across the cathode resistance, which in turn reduces the amplification and gain of the stage. If a second r-f amplifier tube is used, its cathode may be tied to the cathode of the first r-f amplifier, to secure variable bias for both tubes from the same control. In this way, more effective gain control is realized.

(3) *Agc* (*automatic gain control*) is provided through introduction of an *avc* voltage into the grid circuit of the tube. The *avc* voltage is applied through the filter, *R*3 and *C*3, which prevents any residual i-f pulsations in the detector output from reaching the grid of the r-f tube. Capacitor *C*3 is inserted between the lower end of the input transformer secondary and ground to avoid shorting out the *avc* voltage. In elaborate communication receivers, an r-f gain control is provided in addition to the usual manual volume control in the detector or first audio stage. This permits satisfactory adjustment of receiver sensitivity and loudspeaker volume.

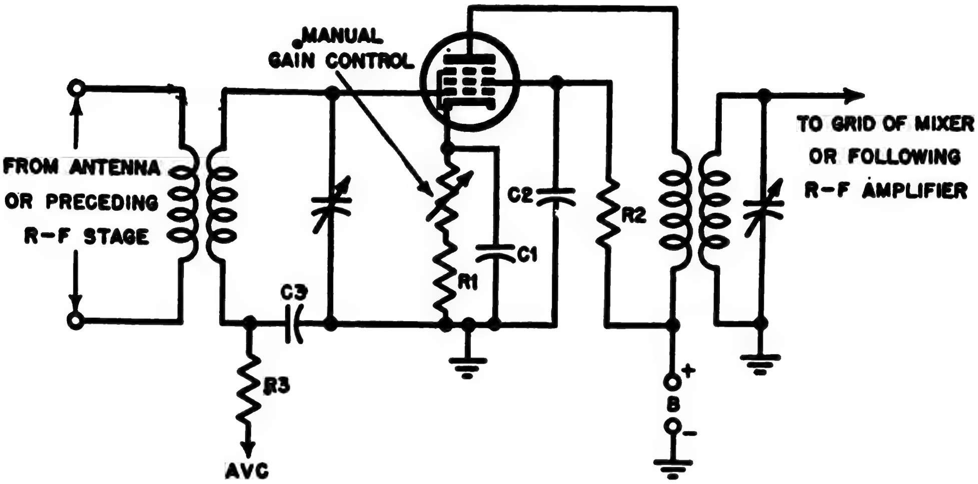


Figure 199. Typical r-f amplifier stage with manual and automatic gain control.

f. Tuning. The principles of tuning and tracking the mixer and oscillator circuits of a superheterodyne receiver have been discussed previously in this chapter. It was pointed out (par. 133) that a constant frequency difference equal to the i-f must be maintained between the mixer and oscillator tuned circuit throughout the frequency range of each band. If this condition is attained, the circuits are said to *track*. For convenience, the tuning capacitors are ganged together, and tracking is achieved by small fixed series and parallel capacitors. Tracking at the high-frequency end of each band is obtained by trimmer (parallel) capacitors, whereas tracking at the low-frequency end is assured by padder (series) capacitors. Padders usually are provided only for the local-oscillator circuit. When an r-f amplifier is used, the only change required in the tuning is the addition of an extra section in the ganged tuning capacitor for each r-f stage. Thus, for one stage of r-f amplification a three-gang tuning capacitor must be used, one section for the r-f tuned circuit, one for the mixer circuit, and one for the local-oscillator circuit. If a two-stage r-f amplifier is utilized, a four-gang tuning capacitor is required, for a three-stage r-f amplifier, a five-gang capacitor, and so on. For proper tracking, the r-f sections of the ganged capacitors are provided with trimmers.

g. Push-button tuning.

(1) Push-button tuning facilitates quick selection of one of a number of preset (fixed-tuned) frequency channels. This is frequently of importance in military communications when no time can be wasted on tuning adjustments, when interference is present on one of the assigned frequencies, or when a quick change must be made to some stand-by frequency. Push-button tuning systems can be either *electrical* or *mechanical*. In electrical systems, the resonant frequency of each tuned circuit is adjusted by switching the proper capacitor or coil into the circuit. In the mechanical system, the main gang capacitor is rotated either manually or by motor to the position corresponding to the desired frequency.

(2) When the push button is depressed in an electrical system, the resonant frequencies of the oscillator, mixer, and r-f amplifier tuned circuits must all be adjusted to the proper values for the reception of the desired transmitter signal. This can be done by substitution of the proper tuning capacitor or inductor, by adding extra capacitors or inductors to the circuit, or by adjustment of iron-dust cores in coils (slug tuning). If capacitors are inserted, they are in the form of trimmers, which can be *pretuned* to the proper frequency when alining the push-button system. In coil substitution, slug tuning is utilized to pretune each coil. An iron-dust core can be moved in and out of the coil by turning a threaded shaft to which the core is fastened. By adjusting these slugs manually, the inductance of the coil, and therefore of the frequency, can be preset. Depressing the push button then will switch the properly tuned coils into the various tuned circuits. Finally, the push button can be arranged for direct slug tuning, when it will move the iron-dust cores of the r-f amplifier, mixer, and oscillator coils into prearranged positions for each station selected. This is accomplished by a ratchet-and-cam mechanical system, connected to the shafts on which the iron-dust cores are mounted. In electrical systems, the proper coils or capacitors usually are connected into the tuned circuits by multiple switches fastened to the buttons themselves. Some switching arrangements, however, make use of relays and electrically operated contactors. Figure 200 shows a typical slug-tuned oscillator assembly in a modern military receiver.

(3) In simple mechanical systems, the pressure on the push button is utilized directly for turning the shaft of the main tuning capacitor to the desired position. In one popular arrangement the push button is in the form of a spring-loaded plunger to which are attached rods, the length of which can be adjusted to the correct value for each desired station. The capacitor shaft terminates in a flat piece of metal. When the button is depressed, the rods make contact with the metal plate and rotate it. The extent of the rotation depends on the length of the rods and their relative inclination. In more elaborate systems, a motor is geared to the shaft of the tuning capacitor for driving it. A special control device determines the direction and amount of rotation of the motor and so of the capacitor shaft for each station selected. Motor-driven *rotary switches* also are oc-

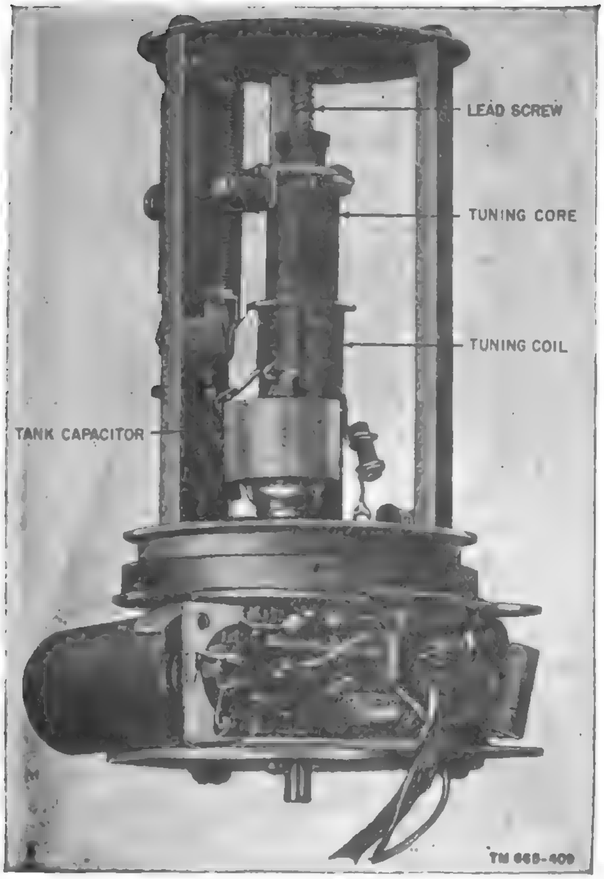


Figure 200. Slug-tuned oscillator coil.

casionally used. Motor-driven systems are especially suited for remote-control tuning of receivers.

150. Power Supply

a. General.

(1) Operation of vacuum tubes and other components of a receiver requires a source of energy which is the function of the power supply. The filaments of vacuum tubes can be heated by low-voltage a-c or d-c. The plates and screen grids, however, require essentially pure d-c of relatively high voltage for proper functioning. The power supply must be capable of furnishing these various voltages efficiently.

(2) A variety of power supplies can be utilized, depending on requirements (see TM 11-663). For small, low-power receivers and receiver-transmitters, batteries frequently are used. In larger portable and mobile equipments, the high-voltage d-c plate power is furnished by dynamotors or vibrators which are energized by storage batteries or hand generators. The filaments are supplied directly from storage batteries. Large semiportable installations generally are equipped with gasoline-driven generators, which provide a 110-volt, 60-cps, a-c power source. Fixed installations ordinarily use the available commercial a-c line supply. In this section, only a brief review is given of d-c and a-c power supplies used for low-power receiver applications.

b. Batteries. A *battery power pack* consisting of dry batteries may be used to furnish energy to small portable receivers of the handy-talkie and walkie-talkie type. The battery pack contains all necessary filament (A supply), plate (B supply), and grid (C supply) batteries for operation of the receiver. Separate filament, grid, and plate batteries are used in some receivers. Battery receivers generally utilize vacuum tubes that have low plate currents and require low filament voltages. In this way the current drain from the batteries is kept low, and continuous operation for several hours is possible, before the batteries must be replaced. Because batteries supply d-c, no rectifier and filter circuits are required in battery sets. In more elaborate receivers where relatively large voltages and currents are required, batteries have the disadvantage of being heavy and expensive to replace.

c. Dynamotor. A dynamotor is a combination small motor and generator, mounted on a common frame, which can obtain a high-voltage d-c output from a low-voltage d-c supply. The armature of a dynamotor carries two windings, each connected to a commutator at opposite ends of the shaft. A common single field winding is used to provide the magnetic field for the motor and generator portions of the unit. One armature winding, when energized by a low-d-c voltage (6- or 12-volt storage battery), produces the driving force to rotate the shaft. The other armature winding generates a high a-c voltage when rotated within a magnetic field. This high a-c voltage is changed to d-c by a commutator connected to the generator winding. Dynamotors are well shielded and equipped with interference suppressor filters in the high-voltage leads to smooth out the current and prevent radio interference caused by sparking between brushes and commutator segments. Efficiencies of approximately 50 to 60 percent normally are obtained when daynamotors are used.

d. A-C Power Supply. In fixed and large semiportable field installations, a-c power supplies generally are used. When available commercial 110-volt, 60-cps power lines are used. Otherwise, gasoline engine or diesel engine generators directly furnish the a-c voltage. For field installations, these generators are used almost universally. These generators provide 115/230-volt 60-cps a-c and are used to provide power similar to that supplied by commercial power lines. The output of these a-c supplies first must be transformed to the required voltage before it can be applied to the receiver. In addition to transforming the supply voltage to a lower value for the operation of filaments, and also to a much higher value for the operation of rectifier power supplies, an a-c operated power supply contains both rectifier and filter circuits to supply high-voltage d-c to those portions of the receiver circuitry which require it.

e. Rectifier Circuits.

(1) The ordinary diode vacuum tube is the most frequently used means for rectifying a-c. The *half-wave rectifier* A of figure 201, consists of a single diode connected between the power transformer secondary winding and the load. The load is represented by a simple resistance. Actually, it consists of the filter, voltage divider, and the receiver circuit. In operation, an a-c voltage is applied to the transformer primary which induces a similar voltage across the secondary. This secondary voltage appears at the diode plate. During the positive half-cycles, when the plate is positive in respect to the cathode, the diode conducts, and a current flows from the cathode to the plate through the transformer secondary and the load. During the negative half-cycles of a-c voltage, the plate is negative in respect to the cathode, and consequently no current can flow. It is seen, therefore, that current can flow in only one direction through the load resistance. The shape of the rectifier output wave is shown at the right, in the form of a pulsating d-c voltage.

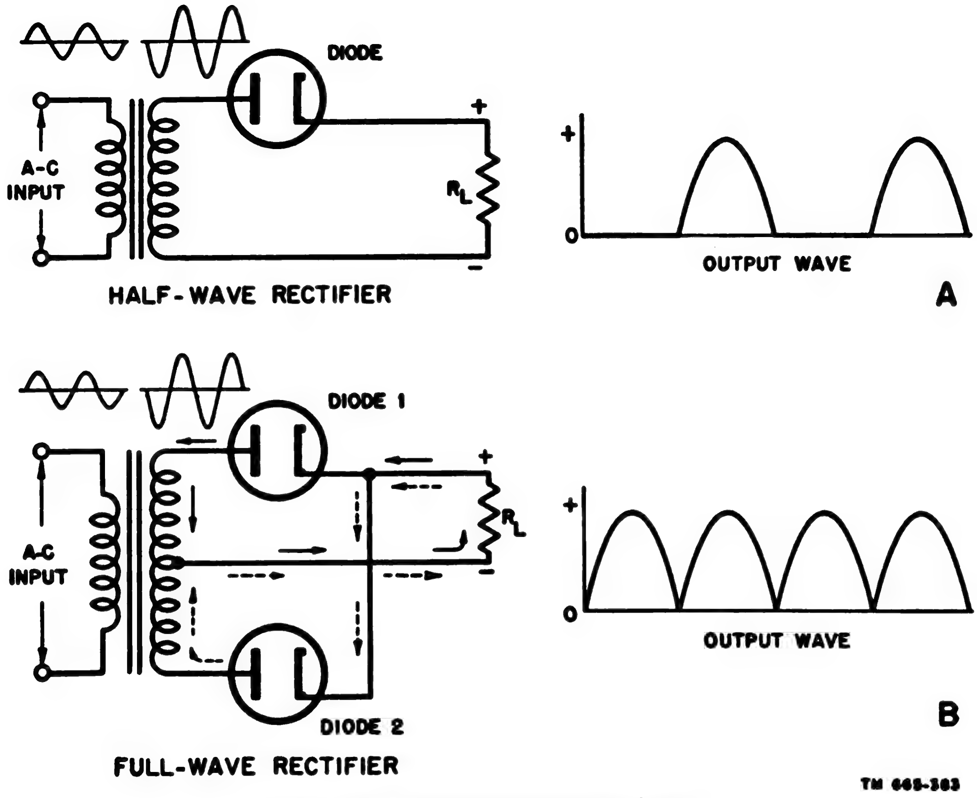


Figure 201. Vacuum-tube rectifier circuits.

(2) The *full-wave rectifier* circuit, in B, which utilizes both half-cycles of the applied a-c voltage is the most frequently used rectifier circuit for receivers. It combines the outputs of two half-wave rectifiers operating on opposite alternations of the full a-c cycle. A power transformer with a center-tapped secondary winding is required. During the first half-cycle of the applied voltage, the plate of tube 2 is positive in respect to the center tap of the transformer. Consequently, a current flows through diode 2, the lower half of the transformer secondary, and through the load, in a direction indicated by the dashed arrows. Current cannot flow through tube 1, since at this moment its plate is negative in respect to its cathode.

(3) During the next half-cycle of the a-c voltage, the polarity of the voltage across the transformer secondary reverses, making the plate of diode 1 positive in respect to the center tap. The plate of diode 2 now is negative, and no current flows through it. Current does flow through diode 1, then through the lower half of the transformer secondary, and through the load, as indicated by the solid arrows. It is seen from the arrows and the output waveshape that current always flows through the load resistance in the same direction. Since there are two d-c pulsations for each complete a-c cycle, the frequency of the pulsations at the output of the rectifier is twice that of the input frequency. This makes possible less output filtering than is required for the half-wave rectifier. Also, with both half-cycles utilized, the average d-c output voltage from the rectifier is higher than for the half-wave rectifier. For the comparatively low voltages required in receivers, the two diodes generally are combined in the same envelope to form a dual-diode.

(4) Compact *selenium* and *copper-oxide* rectifiers of sufficiently high voltage and current ratings often are used to replace vacuum tubes in the rectifier circuits of small receivers. Having no heaters, these metal rectifiers require no heating power. The selenium rectifier is especially popular. For comparable power, the voltage drop across its terminals is much less than for a diode-tube rectifier. Selenium rectifiers generally are built up as an assembly of circular or square disks that are mounted by means of a central hole. The current flows through the disks more easily in one direction than in the opposite direction, and consequently rectification takes place. By combining the proper number and size of disks, practically any voltage and d-c current rating can be obtained. For example, a 100-ma type consists usually of four disks, and measures only 1¼ inches in diameter and ¾ inch in height. Selenium or copper-oxide rectifiers can be used in the same circuits as vacuum tubes. Both half-wave and full-wave circuits are popular, as well as bridge-type circuits.

f. Filter Circuits.

(1) The d-c pulsations from the output of the rectifier must be smoothed out before they can be applied to the plate and grid circuits of vacuum tubes. This smoothing action is obtained by filter networks consisting of choke coils and capacitors (fig. 202). A is a typical *choke-input* filter and B is a *capacitor-input* filter. Only one filter section is shown in each diagram, but several identical sections often are used to improve the smoothing action.

(2) In A, the choke-input inductor readily passes d-c from the rectifier, but opposes any a-c pulsations. Fluctuations in the current that remain after passing through the choke are largely bypassed around the load by the shunt capacitor in the output of the filter. A small *a-c ripple* is still present in the filter output, but is considered negligible if it is less than 1 percent of the steady d-c voltage. A 1-percent ripple can be obtained in a typical receiver, for example, with a 10-henry choke and a 8-μf capacitor. The d-c output voltage of the choke-input filter changes little with changes in load and therefore is said to have good *voltage-regulation.*

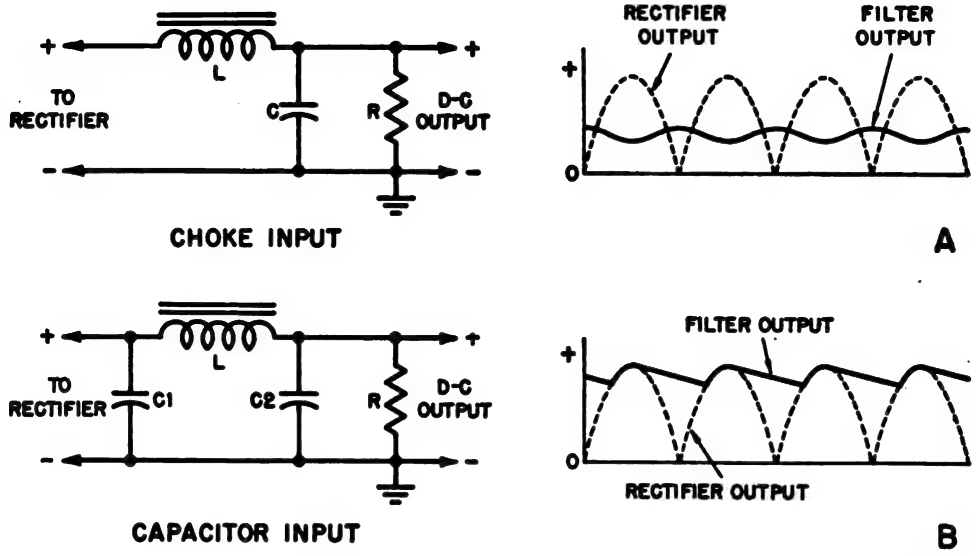


Figure 202. Filter circuits.

(3) The action of the capacitor-input filter, in B, is slightly different. The rectifier output voltage first charges the capacitor to the *peak value* of the pulsations. The capacitor tends to hold this charge between successive pulses, discharging slowly through the choke and load. Consequently, the voltage across the capacitor remains approximately constant near the peak value. Thus, the output voltage of the capacitor-input filter is higher than that of a choke input filter for the same input voltage. The remaining fluctuations of the current are opposed by the series choke, and bypassed to ground by the output capacitor. As before, an a-c ripple remains in the output. The voltage regulation of the capacitor-input filter is considerably poorer than that of the choke-input filter, because the output voltage falls off rapidly with increasing load.

(4) The resistance, *R*, connected across the output of each filter circuit is known as a *bleeder resistor*. Its purpose is to place a minimum load across the rectifier during the time when the receiver tubes are heating up and do not draw any current. In this way, an initial high-voltage surge is prevented when the receiver is turned on. The bleeder also serves to maintain a constant output voltage during changes in load. Finally, the bleeder resistor discharges the capacitors after the set has been shut off, and so helps to prevent dangerous shocks. The resistor may be provided with taps to act as a *voltage divider* for supplying the proper voltages to the different tube electrodes (ch. 2).

151. Reproducers

a. General. In the preceding chapters, the progress of a message spoken into a microphone at the transmitters has been followed through transmitter circuits to the transmitting antenna, from there to the receiving antenna, and finally through the various stages of the receiver to the output of the audio amplifier. The a-f output contains *in electrical form* the original modulation superimposed on the carrier at the transmitter. It is the function of the *reproducer* to convert the a-f current variations in the output stage of a receiver into audible energy corresponding to the sounds originally spoken into the transmitter microphone. Reproducers are *electromechanical* devices which translate the current variations at their input into corresponding mechanical vibrations at the output. These mechanical vibrations, in turn, generate the air-pressure variations which produce the sensation of *sound*.

b. Sound.

(1) Sound is the sensation of hearing caused by waves of vibratory energy striking

the mechanism of the ear and transmitted usually by air. These vibrations can be generated by a great many vibrating bodies, such as vocal cords (speech), the strings of a violin (music), the diaphragm of a telephone receiver, or the paper cone of a loud-speaker. When the diaphragm of a telephone receiver moves to and fro in accordance with the audio-frequency variations of the electrical current that energizes its coils, each outward movement of the diaphragm compresses the air in front of it, and each backward movement rarefies the air in front of the diaphragm. These alternate *compressions* and *rarefactions* travel outward from the telephone receiver as a disturbance, called *sound waves.* When the compressions and rarefactions that comprise sound waves enter the ear, they produce the *sensation* of sound.

(2) The ear of the average person is capable of hearing sound waves vibrating at frequencies from approximately 16 to 16,000 cps. For the purpose of intelligible speech communication, it has been found adequate to transmit and reproduce audio frequencies from about 150 to 3,500 cps. Actual sounds are usually *complex waves* containing many frequencies that are in harmonic relation to each other. The fundamental frequency of these harmonics (or *overtones*) is called the *pitch* of the sound, whereas the harmonics determine the *quality* of the sound. If the high frequencies containing most of the harmonics are not reproduced, the naturalness of the sound is diminished. Finally, the intensity of the sound waves determines the *loudness* which they are perceived by the ear. Depending on the frequency and type of sound, intensity variations of over 100,000,000 to 1 can be heard. This tremendous range of intensity cannot be reproduced by the average loudspeaker. Fortunately, realistic reproduction is attained with a much smaller range of about 100,000 to 1.

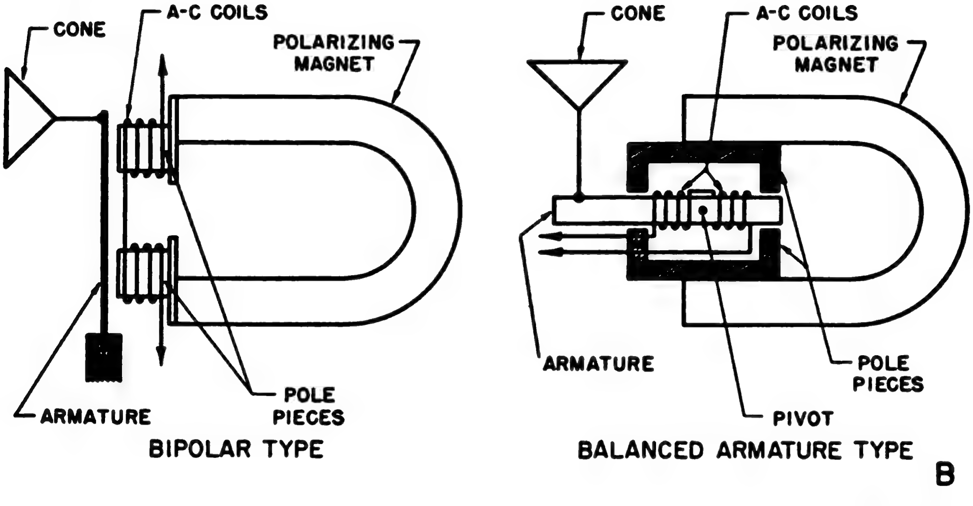
c. *Loudspeakers.*

(1) The loudspeaker must transform electric currents in the audio-frequency range into the corresponding sound waves. Sound waves are radiated best if the loudspeaker makes contact with a large surface of air surrounding it. For this purpose, the electromechanical *driving mechanism* of a loudspeaker is coupled mechanically or acoustically to fairly large cones or horns, capable of pushing large amounts of air in front of them. However, even with efficient designs, these radiators generally cannot transform more than 5 to 10 percent of the electrical input to the loudspeaker into corresponding sound energy. Furthermore, most loudspeakers produce considerable frequency and harmonic distortion of the a-f waveform. Harmonic distortion of the waveform occurs because the complicated loudspeaker driving mechanism cannot be made to act in a strictly *linear* manner. As in detectors, nonlinear operation introduces new (harmonically related) frequencies into the output, which were not present in the input.

(2) Frequency distortion occurs because the loudspeaker assembly and inclosing cabinet break into *mechanical resonance* at several frequencies within the response range. The moving parts of the loudspeaker assembly have a natural frequency of vibration, which depends on their mass, the stiffness of supports, the size of the paper cone or horn, and other factors. A very small audio input produces a very large vibration at this natural frequency, which is usually in the range between 50 to 200 cps. In addition, the speaker cabinet, like any other object, has a frequency of mechanical resonance which decreases the greater the mass of the cabinet. Mechanical resonances tend to accentuate unpleasantly the frequency band near resonance. Other effects tend to reduce the response at certain frequencies. Thus, if an open cabinet or sound board, called a *baffle*, is used to mount the speaker, the sound waves from the front of the cabinet or baffle tend to cancel the sound waves from the back at certain frequencies (*destructive interference*) and so reduce the response. If the baffle or cabinet is made large, this effect usually

occurs at frequencies at the lower end of the response range or below audibility.

(3) In general, the low-frequency response of a speaker improves in accordance with the increase in mass and size of the radiating element and its cabinet. However, these are exactly the conditions for *poor high-frequency response.* This is because at frequencies whose wavelengths are small compared to the diameter of the radiator (high frequencies=small wavelengths), the loudspeaker cone can no longer push the air in front of it efficiently. The mass of the moving mechanism becomes too great to follow the rapid variations at high frequencies.



TM 665-385

Figure 203. Two types of magnetic speakers.

Various refinements have been made in the design of speakers to permit good reproduction at both low and high audio frequencies. In general, however, some compromise must be made between speaker size and desired frequency response, or two differently sized speakers must be used to cover the audio range.

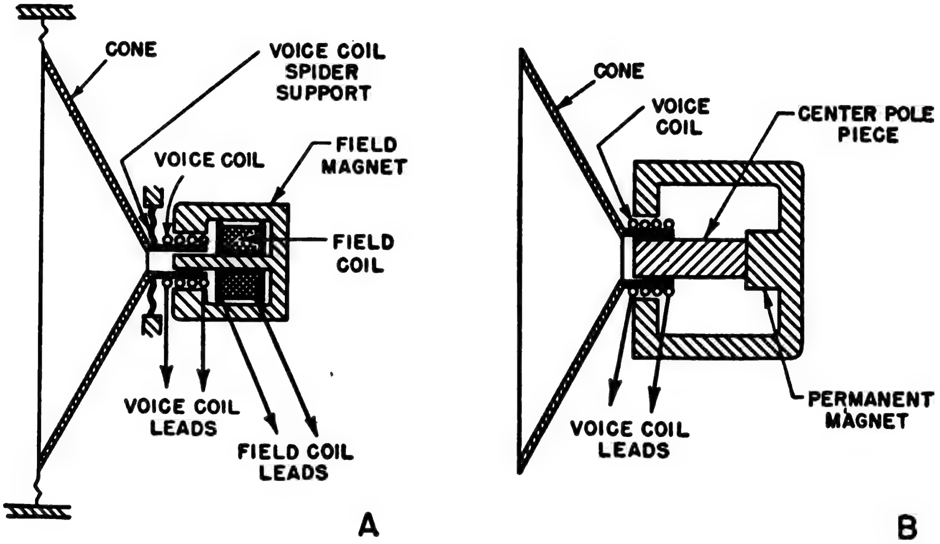
(4) In Signal Corps receivers, the size of the speaker is determined chiefly by the considerations of size and weight, and little attention is paid to frequency distortion, although *harmonic* (nonlinear) distortion must be kept to a minimum for good intelligibility of speech. Although these considerations apply to all speakers, the driving mechanisms which translate the electrical variations into sound waves differ considerably and must be studied separately. Two main types of driving mechanisms are in use: electromagnetic systems, and dynamic (moving-coil) systems. The dynamic types can be classified, according to how they are energized, into electrodynamic and p-m (permanent-magnetic) types.

d. Electromagnetic Speakers. The earliest speakers were of the *electromagnetic* type (A of fig. 203). These are essentially large versions of telephone receivers or headphones and use the same type of driving movement.

(1) A permanent magnet is utilized with a coil of fine wire wound around each *pole piece.* The audio-frequency current flows through these coils in series. An *armature,* consisting of an iron diaphragm and a radiating cone, is mounted in the magnetic field of the permanent magnet near the pole pieces. The magnet exerts a *constant* pull on the armature, so that the diaphragm is under tension. Depending on the strength and polarity of the a-f currents, the magnetic field produced by the coils adds to or subtracts from this constant pull on the diaphragm. Its physical position near the pole pieces, therefore, fluctuates in accordance with the audio currents. These fluctuations of the diaphragm are translated into air-

pressure variations by the cone, or horn radiator, mounted on the armature.

(2) An improved type of magnetic speaker is shown in B. Here the armature is balanced in the center of the magnet between the pole pieces. Depending on the polarity of the a-f current flowing through the coils, the armature is pulled either to the right or to the left from the center position. The armature drives either a diaphragm or the cone-type radiator shown. In older types, a diaphragm was utilized over which a horn extension was mounted. More modern types use cone radiators.



TM 665-386

Figure 204. Dynamic speakers.

(3) Magnetic speakers sometimes are used in small portable receivers because they are highly sensitive, and compact. Since the a-c coils are wound with many turns of fine wire, they have a high impedence which approximately matches the plate impedance of audio output tubes. Consequently, no output transformer is required as for other types of speakers, and the speaker windings are connected directly in series with the plate circuit of the power amplifier. The bulk and cost of the output transformer can be an important factor in small portable radio receivers. The chief disadvantage of magnetic speakers, which has made them practically obsolete for general applications, is their *low acoustic output*. Although they are highly sensitive, they are overloaded easily. For large audio inputs, the mechanism becomes highly nonlinear, and the output becomes very distorted. The undistorted output of such a speaker is very small, particularly at the lower frequencies.

e. Dynamic Speakers. Most modern loudspeakers are of the *dynamic* type, in which a *voice coil* carrying the voice currents moves in and out of a strong surrounding magnetic field. The two basic types of dynamic speakers, the electrodynamic and the permanent-magnetic, or p-m, are shown in A and B, respectively, of figure 204. Except for the manner in which the magnetic field is produced, the action of these two types is identical. Dynamic speakers can provide high acoustic output with little harmonic distortion. Their frequency response can be made substantially uniform over the entire audio range. They are the most rugged speakers available. The discussion is based on the electrodynamic speaker, shown in A.

(1) As is apparent from the figure, a large electromagnet is used which has a central pole piece around which a coil of many turns is wound. This coil, which energizes the magnet, is called the *field coil*, and the entire magnet assembly is known as the *field magnet*. In the narrow pole gap of the magnet a small coil is suspended, consisting of a few turns of wire

wound around a paper or plastic form. This so-called *voice coil* carriers the audio currents from the output of the a-f amplifier. At one end of the voice coil is mounted a fairly large cone radiator made of stiff paper, treated cloth, or plastic material. The cone is held around its edges by a flexible suspension ring fastened to the metal framework of the speaker. At the other end of the moving assembly, another suspension keeps the voice coil in a central position in respect to the pole piece. This suspension, mounted at the juncture of the cone and voice coil, is known as the *spider*. It is constructed of flexible material, and permits forward or backward (longitudinal) motion of the voice coil, but no lateral (sideways) motion. The entire cone and voice-coil assembly is, therefore, free to move as a unit in a *longitudinal* direction. The clearance between the voice coil and the central pole piece is made small to concentrate the magnetic flux in the gap.

(2) When the field coil is energized by d-c of several watts power, a strong magnetic field is produced between the pole pieces of the electromagnet. The magnetic field produced by the a-f currents in the voice coil is at right angles to the field of the electromagnet. The two fields attract or repel each other, depending on the strength and polarity of the audio currents. Since the position of the electromagnet is fixed, the attraction or repulsion of the fields produces an inward or outward movement of voice coil and cone assembly. The movements of the voice coil can be made proportional to the strength of the a-f currents through it. The voice-coil vibrations, in turn, move the radiating cone, thus producing corresponding sound waves.

(3) The field coil which energizes the electromagnet generally is connected either in series or in parallel with the filter circuit of the rectifier power supply, and so is provided with fairly well filtered d-c. In the series connection, the field coil is used as an additional filter choke, and has a low-resistance winding to cut down the voltage drop across its terminals. In the parallel connection, the field coil acts as a bleeder, and must have a high-resistance winding to avoid excessive shunting. To neutralize the a-c ripple of the current flowing through the field coil, which causes hum, most speakers have an additional hum-bucking coil connected in series-opposing with the voice coil. Both the voice coil and the hum-bucking coil pick up a hum component from the field coil. However, since the hum-bucking coil is connected in series-opposition to the voice coil, its field cancels the hum component of the voice-coil field without affecting the a-f voice-coil currents.

f. Permanent-Magnet Speakers. In the *p-m* dynamic speaker shown in B, a permanent magnet is utilized to generate a strong magnetic field instead of an electromagnet. Highly efficient magnetic materials have been developed which provide high magnetic flux with relatively small-sized magnets. One very popular magnetic material is an alloy of *al*uminum, *ni*ckel, and *co*balt called *alnico*. As shown in the figure, the magnet is mounted to the inside back portion of the frame, so that it is in series with the magnetic circuit. The pole pieces concentrate the flux around the voice coil. The action of the p-m speaker is the same as that of the electrodynamic speaker discussed above.

g. Output Circuits.

(1) Loudspeaker output circuits are designed to transfer efficiently the a-f power from the audio output tubes to the voice coil of the loudspeaker. As previously explained (ch. 2), a power source delivers maximum energy to its load when the internal impedance of the source is equal to the load impedance. Consequently, for maximum power transfer from the output tube to the speaker, the voice-coil impedance should be made equal to (or *match*) the plate resistance of the output tube. This is not possible, however, for several reasons. To insure sufficient lightness and rugged construction in the small space available, the voice coil is wound with a few turns of low-resistance wire. The impedance of the average voice coil at low frequencies, therefore, is generally from 2 to 8 ohms. This in-

cludes the resistance of the winding as well as the inductive reactance, which varies widely with frequency and the acoustic loading of the speaker. In contrast, the plate impedance of the output tube varies between 2,000 and 10,000 ohms, depending on the type of tube and output circuit. Obviously, very poor power transfer would result if the voice coil were directly connected into the plate circuit of the output tube. In addition, the output from the tube would be badly distorted.

(2) To achieve the proper *impedance match* between the voice-coil impedance and the plate impedance of the tube, an *output transformer* with a step-down ratio is utilized in the output-tube plate circuit. By use of a transformer with the proper turns ratio, the low voice-coil impedance across the secondary winding will be *reflected* as a high impedance across the terminals of the primary winding to match the plate impedance for optimum operation. Figure 205 shows two typical output circuits with an output transformer. The circuit in A is called *single-ended*, since only one output tube is utilized. The output transformer is connected in series with the plate and the d-c plate-supply voltage. It is a step-down transformer with many turns in the primary circuit, and fewer turns in the secondary circuit. In practice, the voice-coil impedance is *not* matched to the value of the plate resistance of the tube, since this would operate the tube in a part of its characteristic where considerable distortion is present. To avoid this distortion, a part of the available power is sacrificed. It is found that a good compromise between power output and distortion is reached when the plate-load impedance (of triodes) is made from two to three times the value of the plate resistance of the tube. The value of the *optimum load impedance* for a particular tube and type of operation is given in tube manuals. The voice-coil impedance is matched to the value of this optimum load impedance.

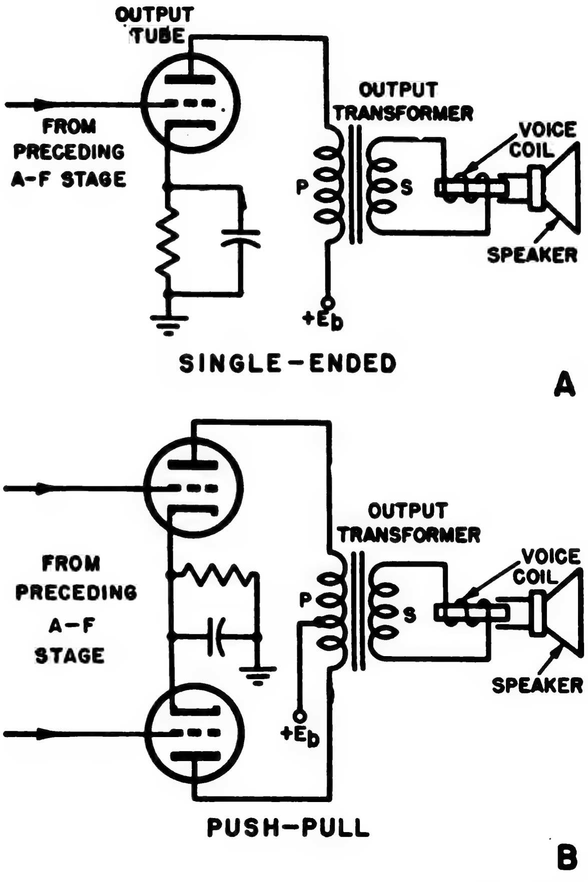


Figure 205. Loudspeaker output circuits.

(3) In B, showing a triode *push-pull* output circuit, the plate circuits of the two tubes are connected in series through the output transformer. The transformer is provided with a center tap on the primary to permit feeding equal d-c plate voltages to the tubes from the common power supply. The primary winding must have a sufficient number of turns—considerably more than in a single-ended transformer—that each *half* of the winding matches the recommended plate-load impedance of one tube. Equivalently, the *full* winding must match the recommended *plate-to-plate load impedance* of *both* tubes. The *plate-to-plate load impedance* for two tubes is generally from approximately one and a half to three times the value for a single tube. The optimum value for low distortion is given in tube manuals for a variety of

operating conditions. The output transformer must match the voice-coil impedance to this optimum plate-to-plate load impedance.

(4) As previously explained, the *impedance ratio* of a transformer is approximately equal to the *square of the turns ratio.* Expressed differently, for a desired impedance ratio between primary and secondary, the *turns ratio* between primary and secondary must be equal to the *square root of this impedance ratio.* The mathematical formula is

$$\frac{Z_p}{Z_s}=\left(\frac{N_p}{N_s}\right)^2 \text{ or } \frac{N_p}{N_s}=\sqrt{\frac{Z_p}{Z_s}}$$

where

Z_p = the primary impedence = recommended plate-load impedance,

Z_s = the secondary impedance = loudspeaker voice-coil impedance,

N_p = the number of turns on the primary winding,

N_s = the number of turns on the secondary winding,

N_p/N_s = the primary-to-secondary turns *ratio.*

(5) For example, assume that it is desired to find the turns ratio required to match a 10-ohm voice-coil impedance to a 10,000-ohm recommended plate-load impedance of a single-ended output stage. The output transformer requires a primary-to-secondary turns ratio equal to

$$\frac{N_p}{N_s}=\sqrt{\frac{Z_p}{Z_s}}=\sqrt{\frac{10{,}000}{10}}=\sqrt{1{,}000}=31.6$$

This means that the primary winding must have 31.6 times as many turns as the secondary winding.

(6) As another example, the recommended plate-to-plate load impedance of a push-pull output stage is 9,000 ohms, and the output transformer has a primary-to-secondary turns ratio of 39. What should be the voice-coil impedance of the loudspeaker connected across the secondary to match the recommended primary load impedance?

$$\frac{Z_p}{Z_s}=\left(\frac{N_p}{N_s}\right)^2 \quad (39)^2=1{,}520$$

and therefore,

$$Z_s=\frac{Z_p}{1{,}520}=\frac{9{,}000}{1{,}520}=5.9 \text{ ohms}$$

A voice-coil impedance of 6 ohms, the nearest commercially available value, will match closely the plate-to-plate impedance of the push-pull output tubes.

152. Typical Superheterodyne Receiver

The superheterodyne receiver (fig. 206) is an eight-tube superheterodyne, consisting of one stage of tuned r-f amplification, a pentagrid mixer and local h-f Hartley oscillator, one stage of i-f amplification, a combined detector, *avc*, a first a-f amplifier stage and a push-pull power-amplifier stage. The receiver is operated from the 110-volt a-c line through a full-wave rectifier power supply and filter circuit. The power supply provides both the high-voltage d-c for the plates and screen-grids, and the low-voltage a-c for the heaters of the vacuum tubes. A detailed circuit analysis follows:

a. Antenna Input and R-F Amplifier. A signal intercepted by the receiver antenna is coupled to the grid of the r-f amplifier tube *V*1, through the r-f input transformer, *T*1. The grid-input circuit of the tube is tuned to the desired signal with a tank circuit consisting of the secondary of *T*1 and variable capacitor *C*1. *C*1 is ganged to the mixer and oscillator tuning capacitors. The selected signal then is amplified by *V*1 and fed to the mixer stage through the r-f coupling transformer, *T*2. An *avc* voltage is applied to the grid of *V*1 through *R*1.

b. Local H-F Oscillator. The local oscillator, consisting of *V*7 and associated circuits, generates oscillations higher than the r-f carrier frequency by an amount equal to the i-f (say 456 kc). For this purpose a conventional Hartley oscillator is used, and its output from the grid of triode oscillator tube *V*7 is coupled through *C*22 to injection grid 3 of the pentagrid mixer tube, *V*2. The oscillator is tuned with the ganged tuning capacitor, *C*3. A parallel trimmer capacitor, *C*24, assures tracking at high frequencies. A series padder capacitor, *C*25, is used for low-frequency tracking; it is made adjustable by means of a small parallel trimmer, *C*26.

c. Mixer. The r-f and local-oscillator frequencies are mixed in the pentagrid mixer tube, *V*2.

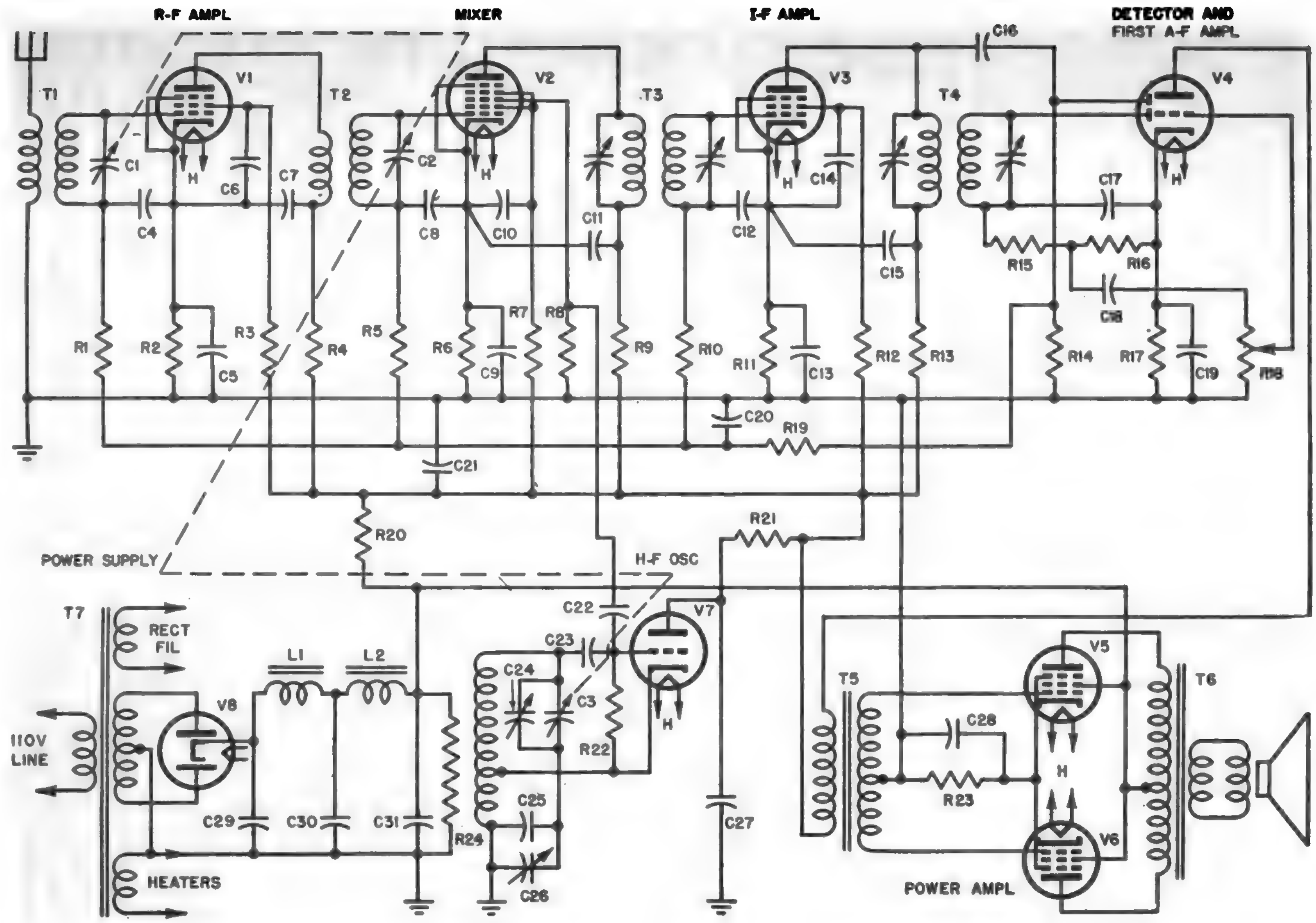


Figure 206. Typical superheterodyne circuit.

The r-f signal is fed to grid 1 of the mixer tube from the tuned input circuit of *T*2 and *C*2. Tuning capacitor *C*2 is ganged with the r-f and oscillator tuning capacitors for single-control tuning. As mentioned, the local-oscillator signal is applied to grid 3 of the mixer tube. The r-f and local-oscillator frequencies are mixed in the electron stream of the mixer tube, producing a number of sum and difference frequencies in the plate output circuit. The i-f transformer, *T*3, in the plate circuit of the mixer tube is tuned to the *difference frequency* (i-f) present in the output of the tube.

d. I-F Amplifier. A conventional i-f stage is used consisting of i-f amplifier tube *V*3, input i-f transformer *T*3, and output i-f transformer *T*4. Both transformers are tuned to the intermediate frequency (456 kc). The i-f signal is coupled through *T*3 to the control grid of the pentode i-f amplifier tube, *V*3. The amplified output from the plate of the tube is coupled through i-f output transformer *T*4 to the diode detector stage.

e. Detector Avc, and First A-F Amplifier. A duplex-diode-triode, *V*4, is used in this stage to combine the functions of a diode detector, *avc*, and first a-f amplifier. The i-f signal is coupled through i-f transformer *T*4 to the lower diode section of *V*4, which acts as the detector. Series resistors *R*15 and *R*16 form the detector load resistance, and *C*17 is the load capacitor. The audio output from the detector is tapped off at the junction of *R*15 and *R*16 and is coupled through blocking capacitor *C*18 and volume control *R*18 to the grid of the triode amplifier portion of *V*4. The volume control is a tapped variable resistor to permit feeding any portion of the a-f output voltage to the grid of *V*4. The a-f signal is amplified by the tube and is coupled to the power amplifier through interstage coupling transformer *T*5. I-f voltage from the plate of the preceding i-f amplifier also is fed through blocking capacitor *C*16 to the upper diode section of *V*4, which rectifies the signal voltage for *avc* purposes. *R*14 is a *separate avc* diode load resistor. The d-c *avc* voltage developed across this resistor is applied to the grids of r-f amplifier *V*1, mixer *V*2, and i-f amplifier *V*3 through the *avc* filter, *R*19 and *R*20, which eliminates the audio component from the rectified *avc* voltage.

f. A-F Power Amplifier. The audio output from the plate of *V*4 is fed to the grids of the power amplifier pentodes, *V*5 and *V*6, through the interstage coupling transformer, *T*5. This transformer is center-tapped to apply the audio signal in opposite phase relation to the grids of the two tubes, a necessary condition for push-pull operation. The output from the power amplifier is coupled to the voice coil of the loudspeaker through the center-tapped output transformer, *T*6. The transformer assures a correct match between the voice-coil impedance and the recommended plate-to-plate load impedance of the amplifier.

g. Power Supply. The 110-volt, 60-cps a-c line input is coupled to the plates of full-wave rectifier tube *V*8 through power transformer *T*7. The transformer carries additional windings to supply the rectifier filament and the heaters of the receiving tubes. The pulsating d-c output from the rectifier tube is applied to a two-stage capacitor-input filter consisting of filter capacitor *C*29, *C*30, and *C*31, and filter chokes *L*1 and *L*2. A bleeder resistor, *R*24, is connected across the filter output to provide a minimum load and improve the voltage regulation.

153. Tuning Indicators

Highly selective modern superheterodyne receivers generally require some form of tuning aid to indicate when the receiver circuits are accurately tuned to the center (carrier) frequency of the incoming signal. Mistuning causes sideband cutting and consequent distortion. Because the *avc* circuit tends to maintain the loudness level of the receiver output, even for considerable mistuning, it is difficult to judge by the ear alone when the receiver is tuned properly. Two types of *tuning indicators* are in general commercial use—meter indicators and electron-ray, or *magic-eye*, indicators. However, the Signal Corps uses only the tuning meter type of indicator.

a. Meter Indicators. The simplest type of tuning indicator is an ordinary direct-current meter connected in series with the plates of the *avc*-controlled *i-f* or *r-f* tubes, or both. The range of the meter may be from a few hundred microamperes to a few milliamperes, depending on receiver sensitivity. When the receiver tuning is off frequency, the grid bias on the *r-f* and *i-f* tubes is low, and consequently the plate current is high. As the receiver is tuned more closely, the *avc* circuit applies increasing negative bias to the tubes, and the plate current *decreases*. The correct tuning point is indicated by minimum plate current registered by the meter. Since the pointer deflection decreases as the correct tuning point is approached, meter-type tuning indicators often are mounted in an upside-down position. Scale calibration points may be provided to indicate the relative signal strength. In some receivers, the tuning meter reads the unbalanced current of a bridge circuit connected across the *avc* line. A *forward* meter indication is obtained in this case, and the meter can be mounted in the conventional position.

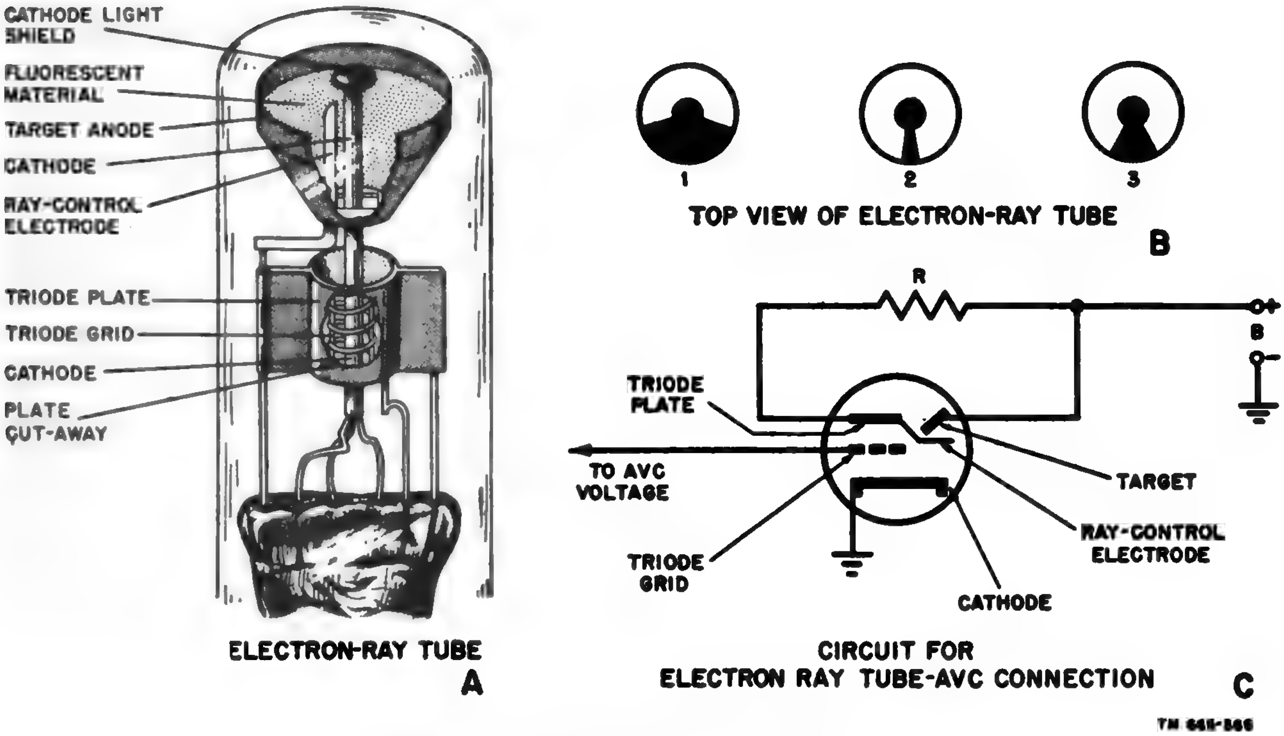


Figure 207. Electron-ray tube tuning indicator.

b. Electron-Ray (*Magic-Eye*) *Indicators.*

(1) Electron-ray indicators are used frequently as visual tuning aids in modern receivers. The tube consists of a double-electrode system combining a miniature cathode-ray tube and an ordinary triode in the same envelope (A of fig. 207). In addition to the triode, two special electrodes are utilized, namely the *target* and the *deflector*, or *ray-control electrode*. The target is connected to the plate voltage supply of the receiver. Operating at a high positive voltage, it attracts electrons from the cathode of the tube. When electrons strike the target they produce a greenish glow on its fluorescent coating. Under these operating conditions, the target appears as a ring of green light.

(2) The deflector or ray-control electrode is mounted between the cathode and the target. It has the form of a thin vertical vane which shades part of the target. When the ray-control electrode is less positive than the target, electrons flowing to the target are repelled by the field of the ray-control electrode and do not reach the portion of the target behind the electrode. Since these shielded portions of the target do not glow, the ray-control electrode casts a shadow on the target. The width of the shadow depends on the relative voltages on the target and the ray-control electrode. When the control electrode is much more negative than the target, the shadow angle is approximately 100°, as shown in 1, B of figure 207. The shadow angle approaches 0° when the control electrode is at about the same potential as the target shown in 2, B. For intermediate relative voltages on the target and control electrode, the shadow has some value between these two extremes, which is 3, B. A dark spot in the center

of the ring of light is caused by the *cathode light shield* which is purposely added to make the deflection more noticeable.

(3) The basic circuit connections of the electron-ray tube are shown in C. The grid of the triode section is connected to the *avc* voltage. When no signal is received, the *avc* voltage is zero; therefore, the bias on the triode control grid is also zero. Consequently, a high plate current flows through the tube and produces a large voltage drop across the plate load resistance, *R*. This voltage drop subtracts from the voltage on the plate, and consequently from that on the ray-control electrode, which is internally connected to the plate. The voltage on the ray-control electrode, therefore, will be much less than that on the target, which is connected to the high-voltage plate supply. For this condition, the shadow angle is a maximum.

(4) When the receiver has been properly tuned to the carrier of a radio station, the *avc* voltage is a maximum, and therefore the triode control-grid bias is highly negative. Consequently, the plate current is low, and the voltage drop across *R* is small. The ray-control electrode has nearly the same voltage as the target, and therefore the shadow angle is a minimum. The greater the strength of the signal, the larger will be the *avc* bias, and the smaller the minimum shadow. The electron-ray tuning indicator, therefore, indicates both correct tuning and signal strength.

154. Summary

a. The superheterodyne receiver differs essentially from the trf receiver in that it changes the frequency of the received signal to a lower, fixed value, at which the tuned amplifying circuits can be designed to operate with maximum stability, selectivity, and sensitivity. It has fewer tunable circuits and is easily adapted to multiband reception.

b. The conversion of the received signal into a lower i-f frequency is based on the *heterodyne* principle.

c. When a modulated radio signal is heterodyned with a locally generated signal, the envelope of the resulting beat frequency (i-f), contains the modulation of the original radio signal.

d. Two r-f signals of different frequency will interact only if they are combined in a *mixer* with a *nonlinear* characteristic. Besides the difference frequency between the two signals, a mixer generates numerous harmonic, sum, and difference frequencies between harmonics. Of these, only the difference frequency (i-f) of the original signals is selected by a tuned circuit in the output of the mixer stage.

e. The principle of frequency conversion inherently provides higher selectivity than a trf circuit. It increases the relative frequency separation between closely spaced adjacent carriers.

f. The basic components of a superheterodyne receiver are the antenna, the r-f amplifier, the frequency converter consisting of mixer and local oscillator, the i-f amplifier, the detector, the a-f amplifier, and the reproducer.

g. *Frequency conversion* is accomplished by vacuum-tube oscillator and mixer circuits. The plate current of the mixer tube is varied at the combination frequency of the signal and local-oscillator frequencies to produce the desired intermediate frequency, which is the difference between the two.

h. Separate mixer and oscillator tubes may be used—triodes, pentodes, or pentagrid mixers. The mixer and oscillator tubes also can be combined in one envelope, as in a triode-heptode, triode-hexode, or pentagrid converter.

i. The local-oscillator and signal voltages can be inductively or capacitively coupled and impressed on the same grid of the mixer (single-electrode input), or they can be applied to two different grids of the mixer (double-electrode input). In the latter, coupling is provided by the common electron stream of the tube.

j. The *conversion transconductance* is the ratio of the i-f current at the output of the mixer tube to the r-f signal voltage applied to the grid of the mixer.

k. The *conversion efficiency*, or *conversion gain*, is the ratio of the i-f output *voltage* from the mixer to the r-f input voltage to the mixer.

l. Triode and pentode mixers operate like plate detectors and are characterized by high conversion gain, low noise level, and low cost. They have the disadvantage of causing undesirable coupling (pulling) between the mixer and the oscillator. *Frequency pulling* is the term applied to the change in the oscillator frequency when the tuning of the mixer input is adjusted.

m. Pentagrid mixers avoid pulling by providing complete isolation between the oscillator and r-f signal circuits. They also have excellent stability at high frequencies.

n. A constant frequency difference (called *frequency tracking*) is maintained between the mixer and oscillator circuits by means of trimmer capacitors at high frequencies, and by *padder* capacitors at low frequencies. These are connected in parallel or in series, respectively, with the main oscillator tuning capacitor.

o. The selectivity, fidelity, and gain of the superheterodyne receiver is controlled to a major extent in the intermediate-frequency amplifier stages.

p. I-f amplifiers can be one-, two-, or three-stage vacuum-tube amplifiers, each stage being provided with an input and output *i-f transformer*.

q. The i-f transformer usually consists of two coupled resonant circuits, whose band-pass characteristics depend on the degree of coupling. If the coupling is greater than the *critical value*, a double-peaked resonance curve results, which provides substantially uniform response between peaks. The band-pass characteristic is controlled by the separation of the peaks.

r. The selectivity of each i-f amplifier stage depends on the Q and the coupling of the i-f transformer. The *over-all* selectivity is proportional to the number of tuned i-f circuits utilized.

s. The gain attained in each i-f stage depends on the required relative bandwidth, the intermediate frequency, and the transconductance, g_m, of the amplifier tube.

t. The selection of the intermediate frequency is a compromise between the desired selectivity and gain on the one hand, and the permissible amount of pulling and *image interference* on the other hand. The higher the i-f, the lower is the selectivity and gain; the lower the i-f, the greater is the possible image interference and pulling.

u. Most superheterodyne receivers use a diode detector, because its linear characteristics give it high signal-handling ability with low distortion. A diode detector, however, has poor selectivity and low sensitivity.

v. Automatic volume control maintains approximately constant signal input to the detector—regardless of signal strength—by making the gain of the r-f and i-f stages less for a strong signal than for a weak signal. *Avc* thus prevents overloading of the r-f, i-f, and detector stages and eliminates extreme variations in loudspeaker volume caused by tuning or fading.

w. An *avc* circuit derives a negative bias voltage proportional to the carrier amplitude by rectifying the carrier with a diode detector.

x. In a delayed *avc* circuit, the application of the *avc* voltage to the grids of the preceding r-f and i-f amplifiers is delayed until the signal strength exceeds a given value.

y. Quiet *avc* eliminates the high background noise present during tuning by muting the receiver between stations.

z. The function of the audio amplifier is to strengthen the a-f output from the detector to a comfortable listening level. One stage of audio amplification usually is sufficient to operate a headset or a small loudspeaker. Several stages may be required to provide sufficient power to operate a large speaker.

aa. The power to operate the speaker is developed in the final audio stage, called the *power amplifier*. The grid excitation voltage needed to operate the power amplifier is provided by one or more stages of *voltage amplification*.

ab. Coupling between a-f stages can be made by means of transformers, impedances (chokes), or resistors and capacitors. Transformer coupling provides additional voltage step-up, but is bulky and expensive. Resistance-capacitance coupling has excellent frequency response. Impedance coupling is used in special applications only.

ac. *Frequency distortion* takes place in an audio amplifier, if the frequencies of the audio band (16 to 16,000 cps) are not uniformly amplified. Some frequency distortion does not reduce the *intelligibility*.

ad. *Harmonic distortion* occurs in a-f amplifiers if nonlinear circuit elements introduce harmonic frequencies into the output which were not present in the input of the amplifier. Beat frequencies between those harmonics cause *intermodulation distortion*.

ae. *Negative feedback* is degeneration of the input signal produced by feeding back a portion of the output voltage from the plate of the output tube to the input of the same or a preceding tube out of phase with the applied voltage.

af. The r-f amplifier in a superheterodyne receiver provides the following advantages: suppression of image interference, improved selectivity, improved signal-to-noise ratio, and isolation between the antenna and frequency-converter stage (reradiation suppression).

ag. Manual sensitivity control often is incorporated into the r-f stage in the form of a variable cathode resistor providing variable bias to the grids of remote cut-off amplifier tubes.

ah. Push-button tuning facilitates quick selection of any one of a number of fixed-tuned frequency channels; it can be of either the electrical or the mechanical type.

ai. The power supply of a receiver must furnish the low a-c or d-c voltages for the heaters of the vacuum tubes, and relatively high d-c voltages for the screen grids and plates.

aj. Small portable receivers are frequently powered by a *battery power pack*, which contains all necessary filament (A-supply), plate (B-supply), and grid (C-supply) batteries.

ak. Dynamotors provide high-voltage d-c plate supply from a low-voltage d-c source (6- or 12-volt batteries). They consist basically of a small motor and generator, both mounted on a common frame. Dynamotors use a common field winding and low- and high-voltage armature windings.

al. A-c power supplies operate from a commercial 110-volt, 60-cps, a-c line, or from gasoline-engine and diesel-engine generators.

am. The output of an a-c supply must be transformed to the required voltage, rectified, and filtered, before it can be used in a receiver.

an. Half-wave rectifiers are simple diodes which rectify alternate half-cycles of the sine-wave input. Vacuum-tube or crystal diodes can be used in the same circuits. *Full-wave* rectifiers utilize both half-cycles of the a-c input by rectifying each with a separate diode.

ao. Filter circuits smooth out the pulsations at the output of the rectifier. Basic filter circuits are *choke-input* and *capacitor-input* filters. Choke-input filters consist of series inductor (choke) at the input, followed by a shunt capacitor; their output voltage is equal to the *average* value of the input pulsations. They have good filtering action and excellent voltage regulation. Capacitor-input filters consist of a shunt capacitor at the input, followed by a series choke, and a shunt capacitor at the output. Their output approaches the peak value of the input pulsations; however, their voltage regulation is poor.

ap. The reproducer converts the electrical audio frequencies in the power output stage into the corresponding audible sound waves.

aq. Loudspeakers can be of the *electromagnetic* or the dynamic (moving-coil) type. The latter are either *electrodynamic* or *permanent magnetic*, depending on whether they use an electromagnet or a permanent magnet to produce a strong magnetic field.

ar. Electromagnetic speakers occasionally are used in small portable receivers, because they are sensitive, and compact, and require no output transformer. However, they have low acoustic output and become overloaded easily, with resulting distorted output.

as. Most modern loudspeakers are of the dynamic type, in which a coil carrying the audio-frequency currents moves in and out of a strong magnetic field. Dynamic speakers provide high acoustic output with little harmonic distortion. Their frequency response can be made substantially uniform over the audio range, and they are of rugged construction.

at. The output transformer in the power output stage of an audio amplifier is designed to match the voice-coil impedance of the speaker to the recommended plate-load impedance of the output stage. When the impedances are matched properly, optimum power transfer will take place from the output stage to the voice coil of the speaker.

au. Tuning indicators give visual indication, when the receiver is tuned to the carrier frequency of the incoming signal. They also give an approximate measure of relative signal strength. Indication is either by means of *meters* or by *electron-ray* indicators, either type being connected in the *avc* circuit of the receiver.

av. Receiver noise can be of the *hiss* type, consisting of a series of overlapping random pulses, or of the *shot* type, consisting of separated single impulses of brief duration and very high amplitude.

aw. Shot or impulse noise can be reduced by i-f noise *silencers*, or a-f noise limiters.

ax. Hiss noise can be reduced by increasing the selectivity of the i-f stages, either by regeneration or by use of crystal or audio filters. This also helps to eliminate *audio-frequency images*, and ~~cuts down~~ adjacent signal interference.

ay. Crystal filters consist of piezoelectric quartz crystals, cut to the intermediate frequency, and inserted into a balanced i-f coupling circuit.

az. Audio filters are simple resonant circuits or band-pass filters inserted between two a-f amplifier stages. They are adjusted to the frequency of the audio beat tone.

155. Review Questions

a. State three disadvantages of the trf receiver which are overcome by the superheterodyne receiver.

b. State briefly the steps involved in reception of an a-m signal by a superheterodyne receiver.

c. Describe the process of frequency conversion in a mixer.

d. Describe another method of frequency conversion.

e. State the relative advantages of triode, pentode, and pentagrid mixers and contrast them with those of combined mixer-oscillator tubes, such as triode-hexodes, triode-heptodes, and pentagrid converters.

f. How can the local oscillator voltage be injected into the mixer? State at least three different methods and how they work.

g. Define *conversion transconductance* and *conversion gain.* What is the conversion gain of a pentagrid mixer, which has a conversion transconductance of 400 micromhos and a plate-load impedance of 15,000 ohms?

h. Which type of converter tube has the poorest noise factor?

i. Explain *frequency pulling*, and how it is avoided.

j. What methods are used to assure frequency tracking between the oscillator and mixer signal circuits? Explain.

k. Define *critical coupling.* Explain what happens when the coupling is greater.

l. If the coupling coefficient of a 456-kc i-f transformer is .03, what are the frequencies of the lower and upper frequency peaks? What is the bandwidth? If the *Q* of the primary winding of the same transformer is 120, and the secondary *Q* is 80, what is the critical *K*?

m. Explain which factors influence the selectivity of each i-f stage.

n. What factors influence the choice of the intermediate frequency?

o. Explain the operation and advantages of the diode detector in a superheterodyne receiver; what are its disadvantages compared to other detectors?

p. What is the purpose of *avc*, and how is it obtained? Does the inclusion of *avc* do away with the need for manual control of volume and sensitivity?

q. What must be done to the a-f output from the detector before it can be made to operate a loudspeaker properly?

r. What determines the number of a-f stages required?

s. Name three methods of a-f amplifier interstage coupling, and state their relative advantages or disadvantages.

t. Define *frequency* and *harmonic* distortion, and explain how each is caused.

u. What is *negative feedback*, how is it obtained, and what does it do?

v. Why is an r-f amplifier used in a superheterodyne receiver? Give four reasons, and justify each in detail.

w. What are the *image frequency* and the *image interference?*

x. A superheterodyne receiver is tuned to an a-m signal of 950 kc. If the i-f is 455 kc, what is the oscillator frequency? At what frequency could image interference occur?

y. How can the sensitivity of the r-f amplifier be controlled by a manual gain control? What type of r-f amplifier tube should be used for this purpose?

z. State the basic principles of tuning a superheterodyne receiver.

aa. Why is push-button tuning used? Describe at least three different methods of *push-button tuning.*

ab. What voltages and currents must be supplied by a power supply? State the type of supply most likely found in a small portable receiver; a mobile receiver-transmitter; and a large fixed installation.

ac. Draw the circuit and explain the operation of a full-wave rectifier.

ad. What is the purpose of filter circuits and of a *bleeder* resistor?

ae. Distinguish between a choke-input and a capacitor-input filter. Describe the operation and advantages of each. Is the output from a filter pure dc?

af. What does a reproducer do? Is it mechanical or electrical? Explain.

ag. Distinguish between different types of loudspeakers, and explain the principles of operation of each type.

ah. Would you use an electromagnetic speaker in a public-address system?

ai. What are the principal causes of frequency and harmonic distortion in loudspeakers?

aj. What is the purpose of the output transformer? What turns ratio (primary-to-secondary) would you choose to match a 2-ohm voice coil to a recommended plate-load impedance of 14,000 ohms?

ak. Describe the purpose and operation of two types of tuning indicators?

al. List various types of receiver noise and their possible causes.

am. Distinguish between noise *silencers* (squelch circuits) and noise *limiters.*

an. What do crystal filters do, and what are their advantage compared with regenerative and noise-limiting circuits?

ao. What is the function of the *phasing capacitor* in the crystal filter?

ap. What is the function of *audio* filters?

CHAPTER 9

C-W DETECTION

156. Need for C-W Detection

a. The receivers discussed in the two preceding chapters were designed for the reception of amplitude-modulated r-f signals. They can receive but not detect continuous waves (c-w signals) unless some modifications are made. The function of the detector circuit in an a-m receiver is to separate the audio-frequency components from the radio-frequency carrier of the incoming signal in order to recover the sound intelligence. Since c-w code signals are not modulated, the intelligence contained in them cannot be recovered by the ordinary detection process.

b. To understand what happens when a c-w signal passes through the detector stage of an a-m receiver, refer to figure 208. A represents the received c-w signal at the input of the detector. This signal is rectified at the detector by the clipping of the negative half cycles of the c-w signal, in B. If a plate detector is used, for example, the a-c plate-current component of the rectified c-w signal appears as shown by the solid line. The average or d-c component of the plate current is indicated by the dotted line. The filter circuit in the output of the detector eliminates all a-c fluctuations for each group of sine waves, and only the d-c component of the plate current remains, as in C. If a pair of headphones is connected in the plate circuit of the detector, this direct current flows through the phone coils and actuates the diaphragm continuously, with the result that no audible tone is heard. Consequently, the detector used in a-m receivers cannot be used for c-w reception.

157. Heterodyne Detection

a. In the reception of c-w signals from a radio telegraph transmitter, some means must be provided for producing an audio-frequency voltage in the detector circuit of the receiver from an unmodulated r-f signal. This is accomplished by the *heterodyne principle*, which was discussed in the preceding chapter. The procedure is to beat the incoming c-w signal with locally generated oscillations to obtain a convenient audio frequency, such as 1,000 cps. This audio frequency is the difference frequency. The difference frequency then is rectified and smoothed out by an ordinary detector. The audio beat note is reproduced through a telephone headset or a loudspeaker.

b. As an example, consider the heterodyne reception of the code letter A (A of fig. 209) which consists of a short burst of c-w energy, followed by a longer burst of c-w energy (dot-dash). Assume that the frequency of the received c-w signal is 500 kc. The locally generated oscillations are adjusted to a frequency which is higher than the incoming r-f signal (in this case, 501 kc), as in *B*. The mixed-frequency voltage, which is the addi-

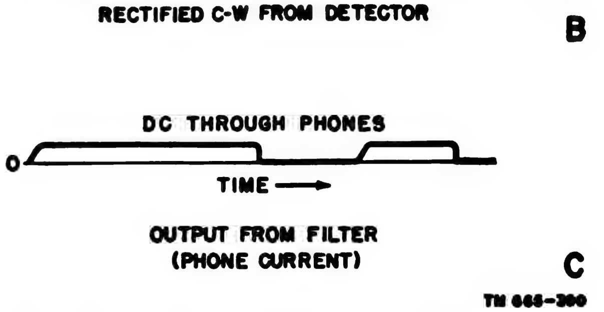


Figure 208. Action of a-m receiver on an unmodulated (c-w) signal.

tion of the c-w signal voltage and the local-oscillator voltage, is illustrated in *C*. Its amplitude (envelope) varies at the beat or difference frequency of 501,000 minus 500,000 or 1,000 cps. Rectification removes the negative half-cycles of the mixed frequency, as in *D*. The peaks of the positive half-cycles follow the 1,000-cps beat frequency. An r-f filter in the detector output removes the c-w signal pulsations so that only the envelope of the rectified pulses remains. The envelope, in *E*, is the 1,000-cps audio beat note. After passing through a reproducer, a 1,000-cps dot-dash tone is heard, which is identified by the operator as the letter A.

c. The heterodyne method of reception has the inherent advantage of very high selectivity, which minimizes interference from adjacent c-w stations. For example, assume that it is desired to receive a c-w signal from a radiotelegraph station operating at 10,000,000 cps, while an adjacent station is operating on a frequency of 10,000,300 cps at the same time. Since the two carrier frequencies differ by only .003 percent, a tuned tank circuit could not be used easily to discriminate between them. However, if heterodyne detection with a local-oscillator frequency of 10,001,000 cps is used, beat notes of 1,000 cps and 700 cps are produced by the desired and undesired signals, respectively. These audio frequencies can be distinguished easily by a selective circuit, since they differ by 30 percent. Even if two incoming c-w signals produce exactly the same beat frequency, they can be separated easily by a slight adjustment of the local-oscillator frequency, which is usually variable. For example, assume that a desired incoming c-w signal with a frequency of 700 kc is mixed with a local-oscillator frequency of 701 kc to produce a 1,000-cps beat note. A radiotelegraph station operating on 702 kc also produces this 1,000-cps beat note, and interference results. However, by adjusting the local oscillator to a frequency of 699 kc for the desired signal, a beat frequency of 1,000 is obtained and the undesired signal (702 kc), now produces a beat note of 3,000 cps. The operator can distinguish easily between these widely differing audio tones.

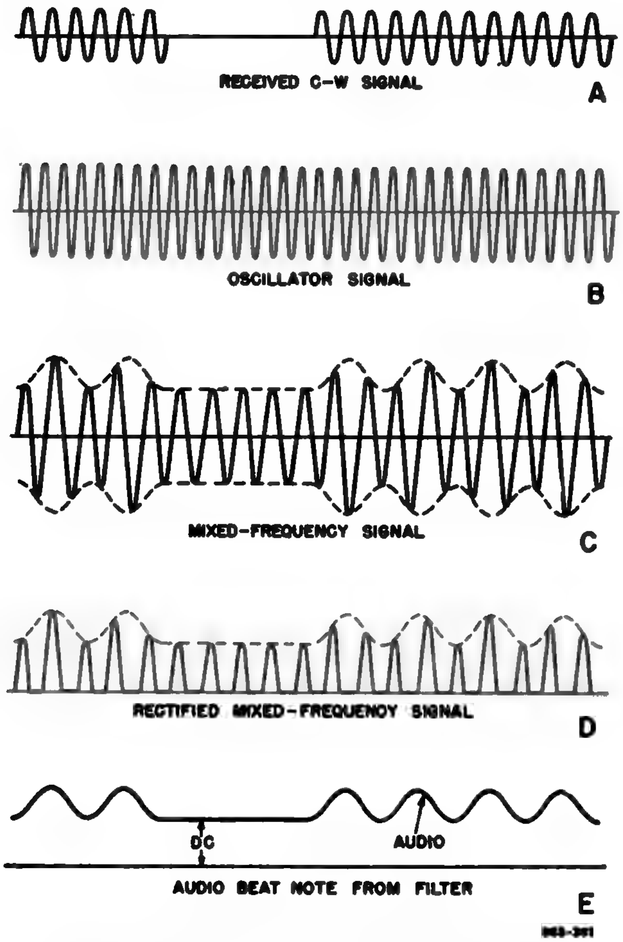


Figure 209. Heterodyne detection of c-w code signal (letter A).

d. Two types of circuits have been developed for heterodyne reception of c-w signals. In one method, the ordinary regenerative detector (par. 118) is operated with sufficient feedback so that it breaks into self-oscillation. The oscillations are mixed with the incoming c-w signal, and a beat note results. This method of beating a self-generated oscillation with an incoming signal of slightly different frequency is called *autodyne reception*. In the second method, a superheterodyne receiver is utilized in conjunction with an additional oscillator. The frequency of this oscillator (*beat-frequency oscillator*) is adjusted to differ, by a convenient audio frequency, from the i-f of the receiver. When the output of the bfo is injected into the receiver i-f system, the mixed frequency is rectified by the second detector, and an audio beat note is produced. In communication receivers, the second method is used ordinarily since the superheterodyne receiver has greater flexibility and somewhat higher sensitivity than the regenerative receiver.

158. Regenerative Detector for C-W Reception

It has been shown (par. 128) that oscillations are produced in a regenerative detector if the amount of energy fed back from its plate-output circuit is sufficient to overcome the losses in its grid-input circuit. The device then functions as an *oscillating detector*.

a. Circuits (fig. 210). The addition of an antenna and a reproducer (headphones) makes each detector a self-contained basic c-w receiver. In practice, however, the regenerative c-w receiver ordinarily contains an r-f amplifier stage ahead of the detector for isolation purposes and increased sensitivity. An additional a-f amplifier stage usually is interposed between the detector and reproducer.

b. Analysis.

(1) The oscillating detector arrangements shown in figure 210 are the same as those used for regenerative detectors, the only difference being that regeneration in the oscillating detector is carried to the point of self-oscillation. These oscillations heterodyne with any signal present in the tuned grid-input circuit (*L-C*) of the detector. For example, assume that the grid circuit of the detector shown in A is tuned to a frequency of 3,001 kc and that a 3,000-kc c-w signal is received. A slight detuning of the grid tank circuit is necessary to produce beats, but it hardly affects the strength of the incoming c-w signal. (If no detuning is present, zero beats result.) Both frequencies are present on the grid of *V1* and are mixed. The

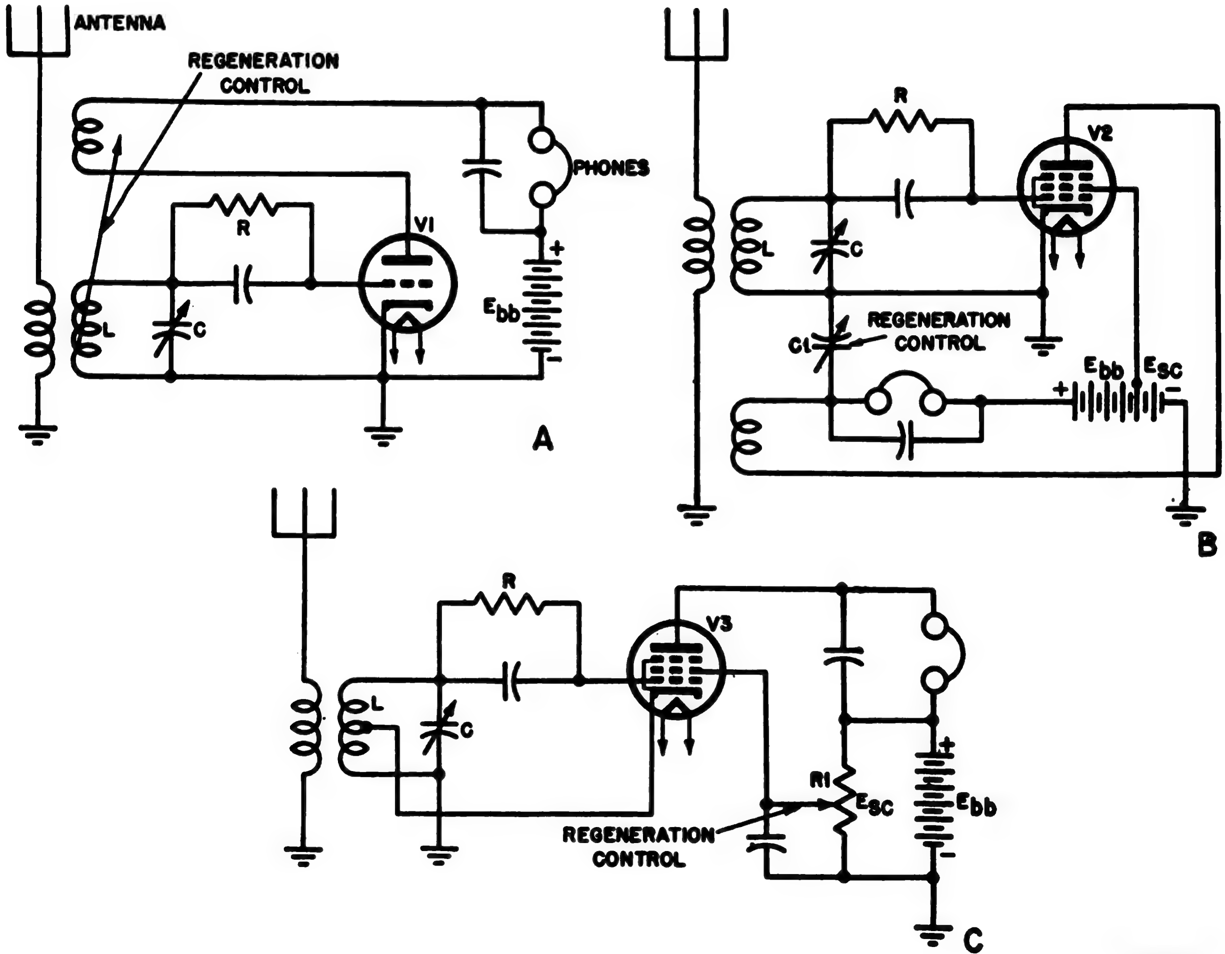


Figure 210. Oscillating detectors for c-w reception.

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resulting beats are rectified by the detector to produce a 1,000-cps beat note in the detector output. The a-f currents in the plate circuit actuate the phones. The oscillating detector, therefore, produces its own oscillations, heterodynes them with an incoming signal, and, finally, rectifies them.

(2) Grid-leak rectification always is used in oscillating detectors. Grid-leak resistor *R* provides proper grid bias for the oscillations and assures high sensitivity. The circuit shown in A uses a triode in a tickler feedback circuit. Adjustable regeneration is provided by varying the physical position of the tickler coil in respect to the grid tank coil, thus charging the mutual coupling between them. When the coupling is so loose that oscillations are barely maintained, a *continuous* audio note is sometimes heard, known as *threshold* or *fringe howl*. This howl will interfere with normal c-w reception. It can be avoided by reducing the detector sensitivity through increased coupling, by using a resistive output load, or by using a pentode which is not subject to fringe howl instead of a triode.

(3) Two pentode circuits are shown, in B and C. The circuit in B is equivalent to the triode tickler feedback circuit in A, except that regeneration control is effected by changing the electrostatic coupling between the plate and grid circuit with variable capacitor *C*1. Fixed magnetic coupling between the tickler (plate) coil and the grid coil is used. The circuit in C utilizes a Hartley circuit for its oscillating portion. Regeneration control is obtained in this case by varying the screen-grid voltage with a tapped voltage divider, *R*1, across the high-voltage supply. The circuit usually is adjusted so that oscillations occur when the screen grid has a fairly low voltage and stop when the screen-grid voltage reaches a value from approximately 20 to 40 volts. If the oscillations are extinguished at higher screen-grid voltages, an annoying thump is heard whenever the circuit goes into or out of oscillation. If the critical stopping point is too low, however, the detector efficiency also is low because of the small plate current.

c. Advantages and Limitations. The regenerative detector is used for the reception of short-wave code signals because it is easy to adjust, and has high sensitivity and good selectivity. At high frequencies, the amount of signal detuning necessary to produce an audio beat note is a small percentage of the signal frequency and causes no trouble. The use of the regenerative detector for low-frequency code reception usually is avoided, however, since at low frequencies the detuning required to produce the proper audio beat frequency is a considerable percentage of the signal frequency. Regenerative detectors have the further disadvantage that they cannot be used in conjunction with superheterodyne receivers, which have become standardized in communications.

159. Superheterodyne Receivers for C-W Reception

The addition of a beat-frequency oscillator is all that is required to make an a-m superheterodyne receiver suitable for the reception of c-w signals. When the oscillator is switched on by the use of the bfo switch, its output heterodynes with any incoming c-w signal to produce an audio beat tone. The receiver can be made ready again instantly for a-m reception by simply turning off the bfo. This easy convertibility from a-m to c-w reception makes it advantageous to use the superior performance of the superheterodyne circuit in a combined a-m and c-w receiver. The arrangement of a communication superheterodyne receiver for both a-m and c-w reception is shown in the block diagram of figure 211. All the stages discussed in chapter 8 are present with the addition of the beat-frequency oscillator. The output of the bfo is shown here, feeding into the input of the detector stage. Alternately, it could be connected to the i-f amplifier. Various methods of bfo injection are possible, but in each case the purpose is to mix the bfo output with the intermediate frequency before detection can take place. The functioning of all stage illustrated (excluding the bfo) is identical with the corresponding stages discussed in the preceding chapter.

160. Beat-Frequency Oscillator

a. Any standard oscillator circuit can be used as a beat-frequency oscillator. Figure 212 illustrates a typical Hartley pentode circuit. Feedback is

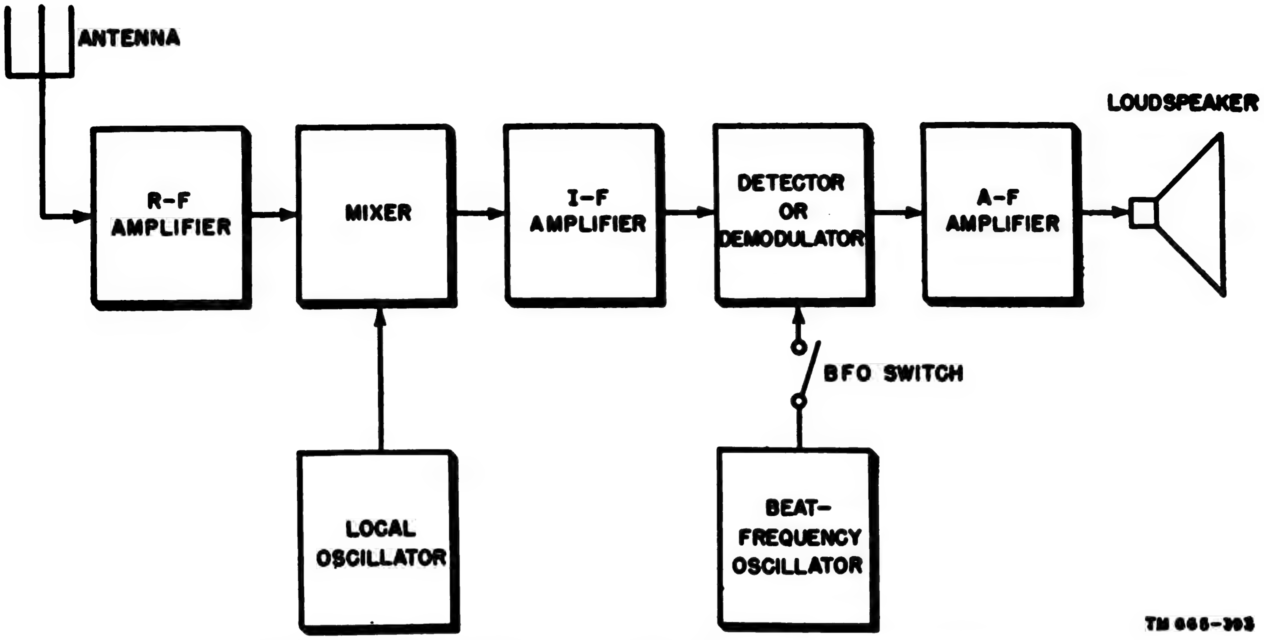

Figure 211. Block diagram of an a-m and a c-w superheterodyne receiver.

obtained from grid to plate through capacitor *C*1. The screen-grid voltage is developed across *R*1. *C*2 is the screen-grid bypass capacitor. *C*3 and *R*2 develop bias for the stage. *C*4 is the oscillator tuning capacitor and *C*5 is its trimmer. The stator of the oscillator tuning capacitor is grounded to avoid detuning of the oscillator because of body capacitance. Detuning frequently occurs when both sides of the tuning capacitors are above ground. The suppressor grid in this circuit is directly connected to ground, since the cathode is not at ground potential. In operation, the main tuning capacitor is preset to the i-f of the receiver, while the parallel trimmer permits detuning the oscillator frequency over a band ranging from a few hundred to about 1,000 cps.

b. The output of the beat-frequency oscillator can be injected at one of a number of points into the i-f amplifier. In the circuit illustrated, the oscillations from the grid coil of the bfo are loosely coupled through *C*6, which has a capacitance of approximately 2 to 5 $\mu\mu$f, to the plate of the diode detector. Here the oscillations are mixed with i-f currents from the secondary of the last i-f transformer, *T*1. The bfo oscillations also can be injected at an earlier stage in the i-f amplifier. One method sometimes used is to take the oscillations from the bfo and feed them directly to the screen grid of the first or second i-f amplifier tube where they are electron-coupled with the i-f through the common electron stream. No coupling capacitor is required in this case. In another method, the functions of the bfo and first i-f amplifier are combined in the envelope of a multi-unit tube. A triode-pentode can be used for this purpose. The pentode section of the tube functions as an ordinary i-f amplifier; the triode section operates as a beat-frequency oscillator which can be switched into the circuit for c-w reception. The oscillations from the triode must be injected into the pentode portion of the tube through some form of inductive or capacitive coupling. Numerous other ways of injecting the bfo output into the i-f amplifier are possible, but in practice it makes little difference which method is chosen.

c. Most modern communication superheterodyne receivers are provided with front panel controls, which permit switching in and out of the *avc* and bfo circuits as well as controlling the pitch of the audio note from the beat-frequency oscillator. When the bfo is switched on for reception of a code signal, the *avc* circuit always should be disconnected, and the manual volume control should be used. This is necessary because the output from the beat-frequency oscillator might reduce the receiver sensitivity through the increased bias voltage developed across the *avc* resistor. After the c-w signal has been tuned in properly, the bfo pitch control should be set at a comfortable audio tone, usually somewhere near 1,000 cps. Some less elaborate receivers do not have a variable pitch control for the bfo, but the frequency of the oscillations can be permanently set by the i-f of the receiver. The c-w signal must first be tuned in by zero-beating it against the output of the beat-frequency oscillator. The receiver must then be detuned slightly to produce a beat signal of a few hundred cycles. The bandwidth of the receiver is generally of sufficient width that the small amount of detuning does not appreciably affect its sensitivity. It has been pointed out that a slight change in pitch of the bfo for an incoming c-w signal sometimes makes it possible to discriminate against nearby interfering signals. Sometimes more serious than adjacent signal interference, however, is the problem of *noise interference* (par. 144), which often mars c-w reception.

d. Audio Images. In a c-w receiver of ordinary selectivity, most incoming code signals within approximately 5,000 cps of the desired signal cause audible beat notes. Since their pitch differs from that of the desired signal, they make it more difficult for the operator to concentrate on the desired signal alone. Also, two adjacent code signals can interfere with each other by producing the same audio-beat note. For example, assume that the bfo is set at 456 kc to give a 1,000-cps beat note when the intermediate frequency is 455 kc. If an interfering signal with an i-f of 457 kc should also be present, it will heterodyne with the bfo signal to produce the same audio tone of 1,000 cps. In other words, the desired a-f signal can be obtained in two different ways. In one, the 1,000-cps audio note is the difference between the bfo signal and the desired intermediate frequency (456 kc minus 455 kc=1,000 cps). In the other, the audio note is the difference between the undesired intermediate frequency and the bfo signal (457 kc minus 456 kc=1,000 cps). In the latter case, the frequency of the undesired i-f is above the desired i-f by an amount equal to *twice* the desired audio frequency. This frequency is known as the *audio image frequency*. The a-f image effect can be reduced by narrowing the bandwidth of the i-f amplifier (increasing its selectivity) so that the heterodyne response at 457 kc is low. Consequently, only a single beat note of the desired frequency is heard. Highly selective circuits, including crystal filters (par. 141) are used for this purpose.

161. Summary

a. A-m detectors do not detect c-w signals because c-w signals are not modulated.

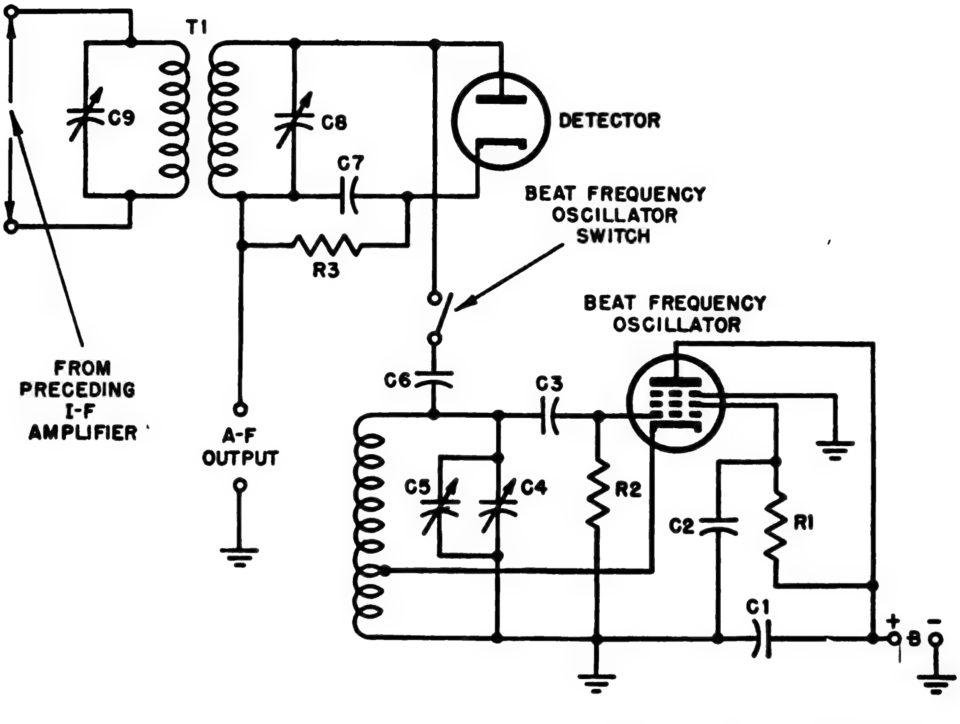

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Figure 212. Typical beat-frequency oscillator circuit.

b. C-w signals are detected by first heterodyning them with the output of an oscillator.

c. The heterodyne method of c-w reception has the advantage of high equivalent selectivity between adjacent interfering signals.

d. Heterodyne reception of c-w signals can be accomplished with a regenerative detector circuit, or by adding a beat-frequency oscillator to an ordinary a-m superheterodyne receiver.

e. If a regenerative circuit is used, it is operated as an oscillating detector, and the resulting self-oscillations are heterodyned with the incoming c-w signal, which is received slightly off-tune.

f. If a superheterodyne receiver is used in conjunction with a beat-frequency oscillator, the frequency of the bfo is adjusted to differ from the i-f of the receiver by a low audio frequency.

g. A superheterodyne receiver can be used for either c-w or a-m reception by simply switching a beat-frequency oscillator into or out of its circuit. The excellent characteristics of superheterodyne reception, therefore, can be taken advantage of for both a-m and c-w reception.

162. Review Questions

a. Describe what happens when a code signal passes through a detector stage of an a-m receiver.

b. What is the basic process of c-w detection?

c. Explain in detail the two methods used for c-w detection.

d. What is *autodyne* reception?

e. How is selectivity improved by heterodyne reception?

f. Why should the *avc* be turned off when receiving code signals?

g. List the advantages and limitations of regenerative detectors for c-w reception.

h. Draw a block diagram of a complete superheterodyne receiver used for c-w reception.

i. How is the bfo signal injected into the i-f amplifier?

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